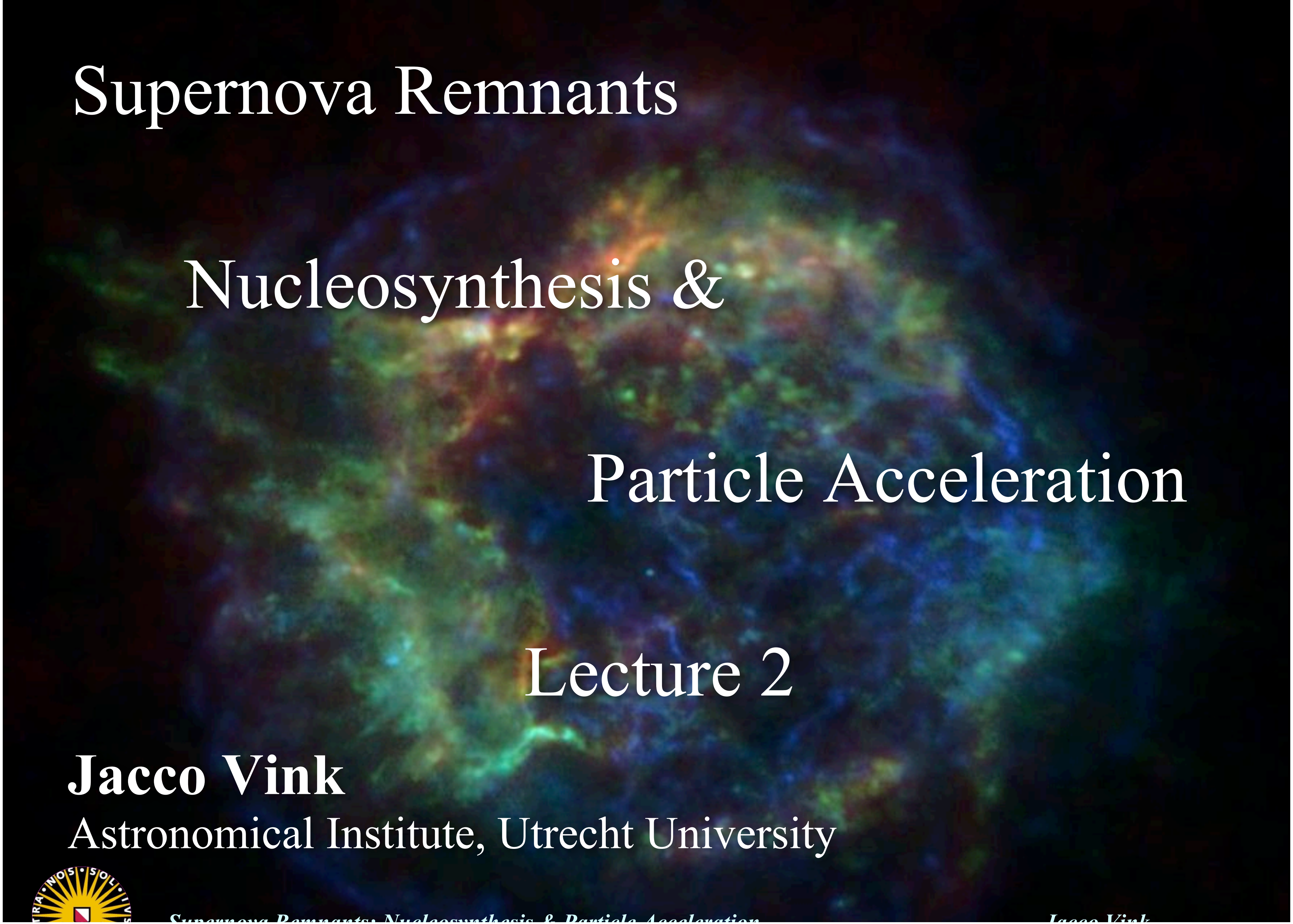


Supernova Remnants

Nucleosynthesis &

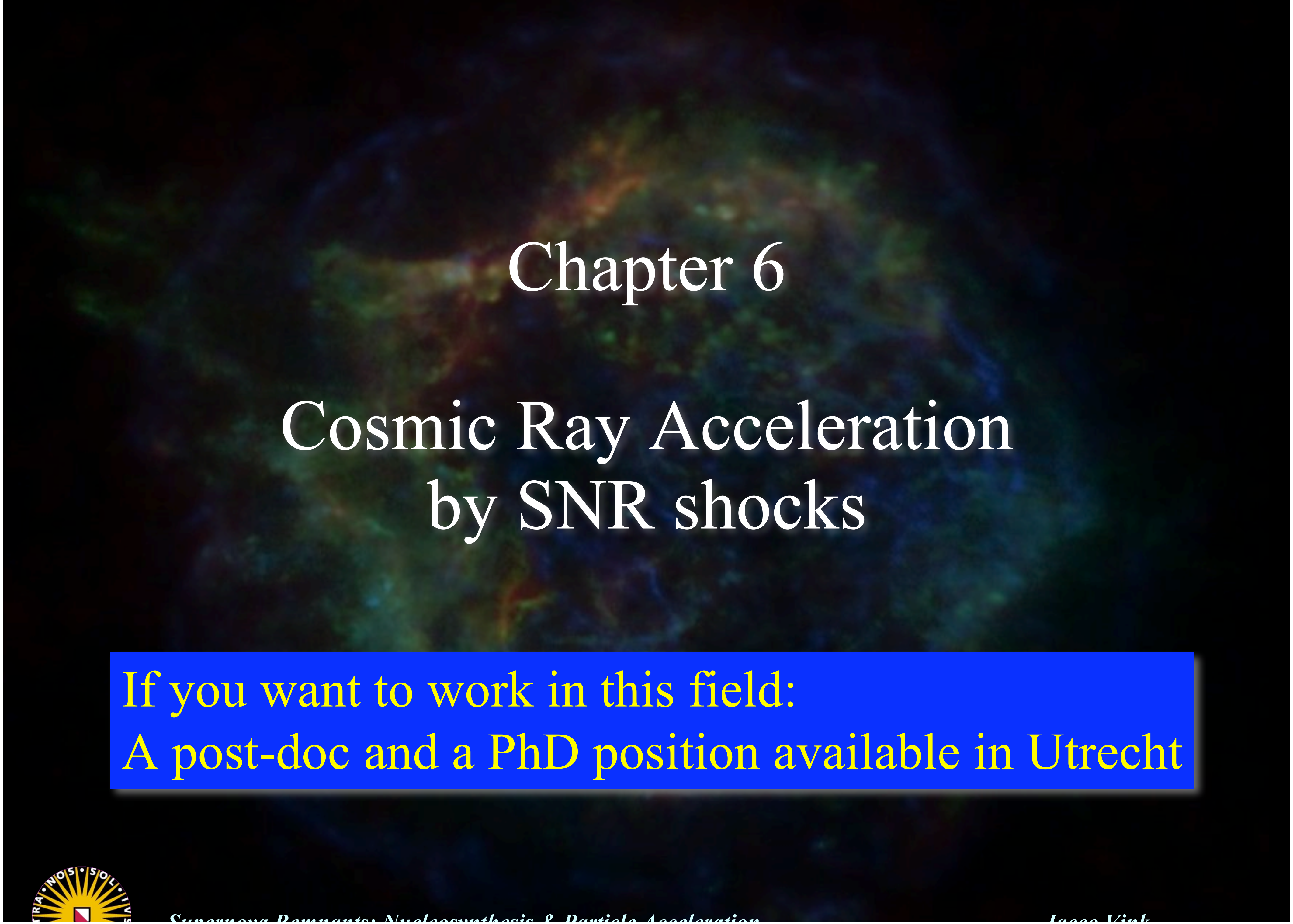
Particle Acceleration

Lecture 2

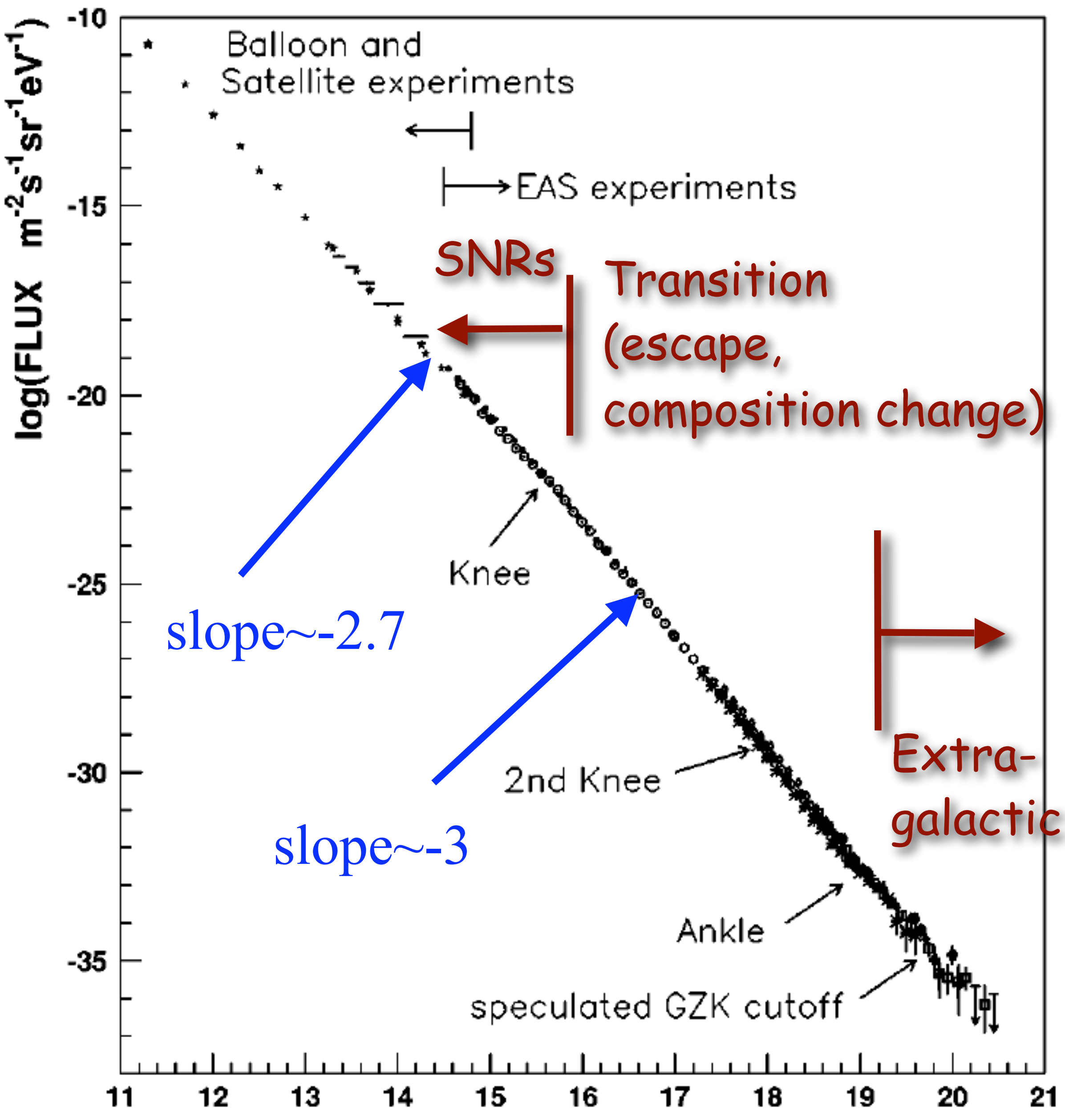
Jacco Vink

Astronomical Institute, Utrecht University

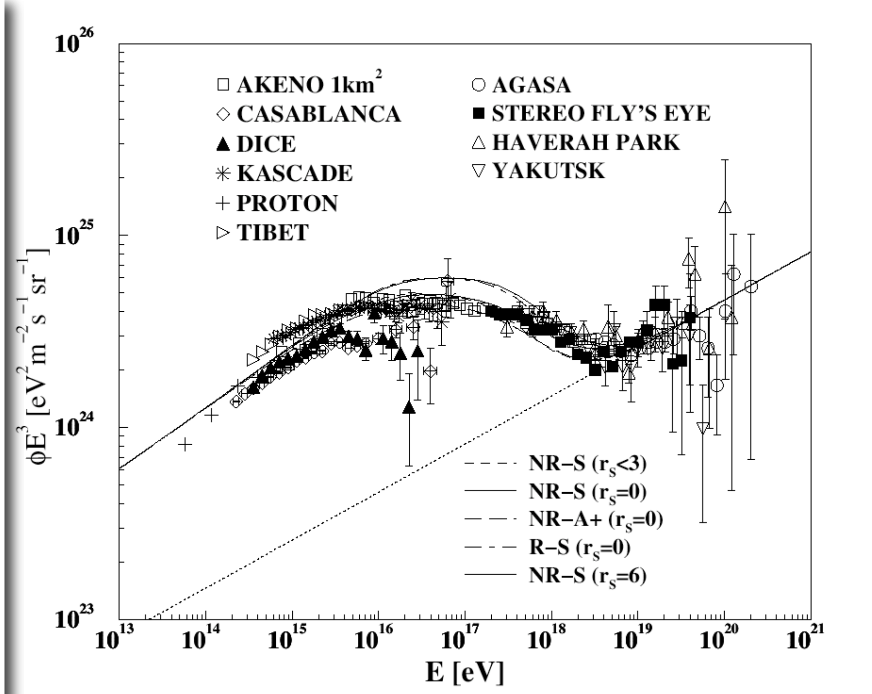
Contents


Chapter 6
Cosmic Ray Acceleration
by SNR shocks
If you want to work in this field:
A post-doc and a PhD position available in Utrecht

Observed Cosmic Ray Spectrum



Nagano & Watson, 2000



Candia et al 2002

Jacco Vink

Supernova remnants and Cosmic Rays

• SNe & SNRs most important source of energy in Galaxy

• But: Can they accelerate up to or beyond the “knee” ?

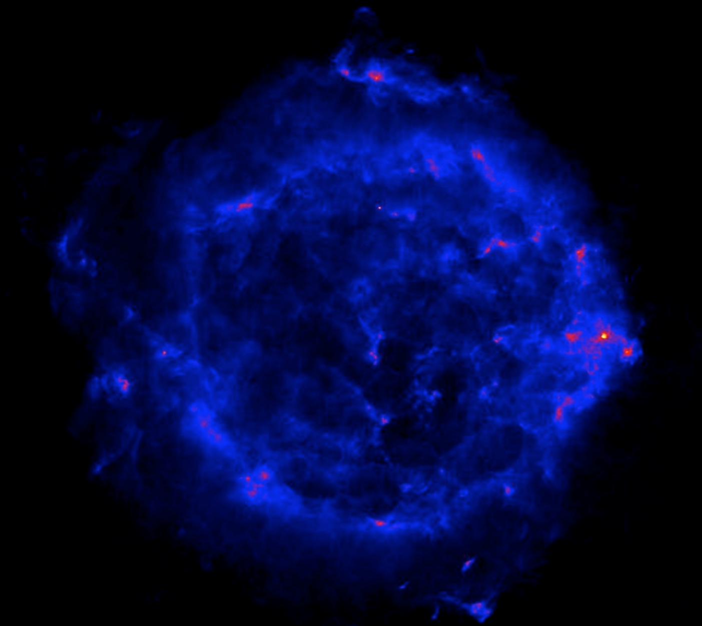
•According to standard shock acceleration/SNR scenario:

No

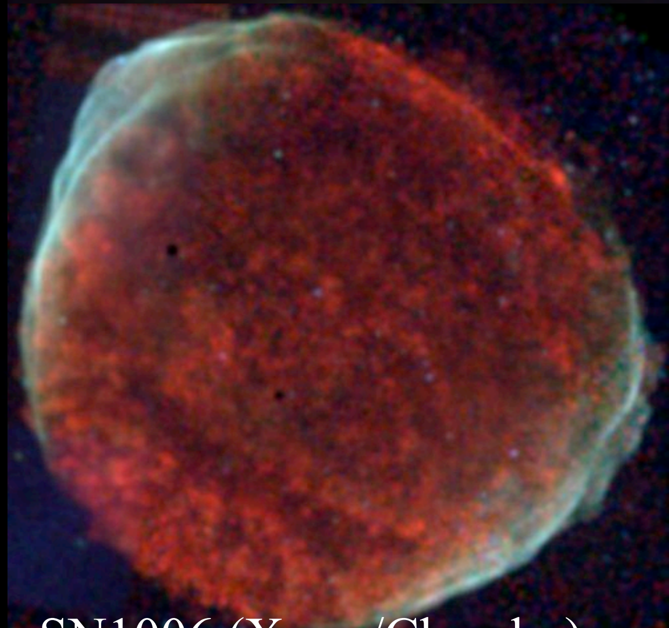
(assuming Galactic B-field, realistic parameters)

(Lagage & Cesarsky 1983)

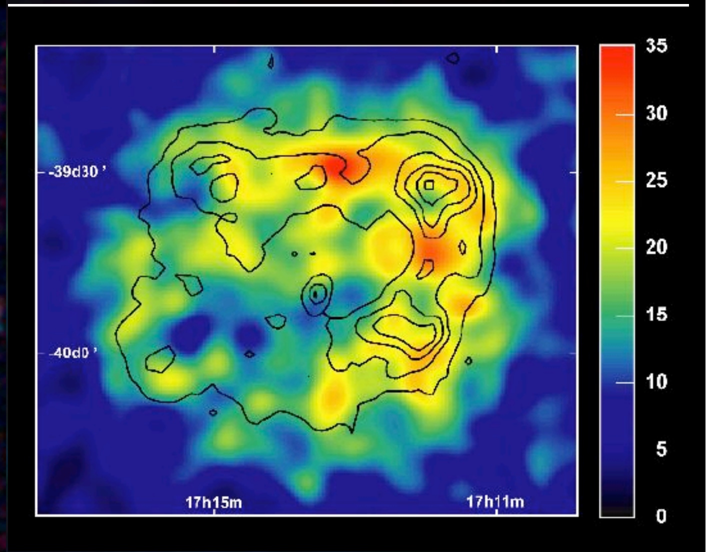
How to Observe Cosmic Rays in SNRs?



Cas A (Radio/VLA)



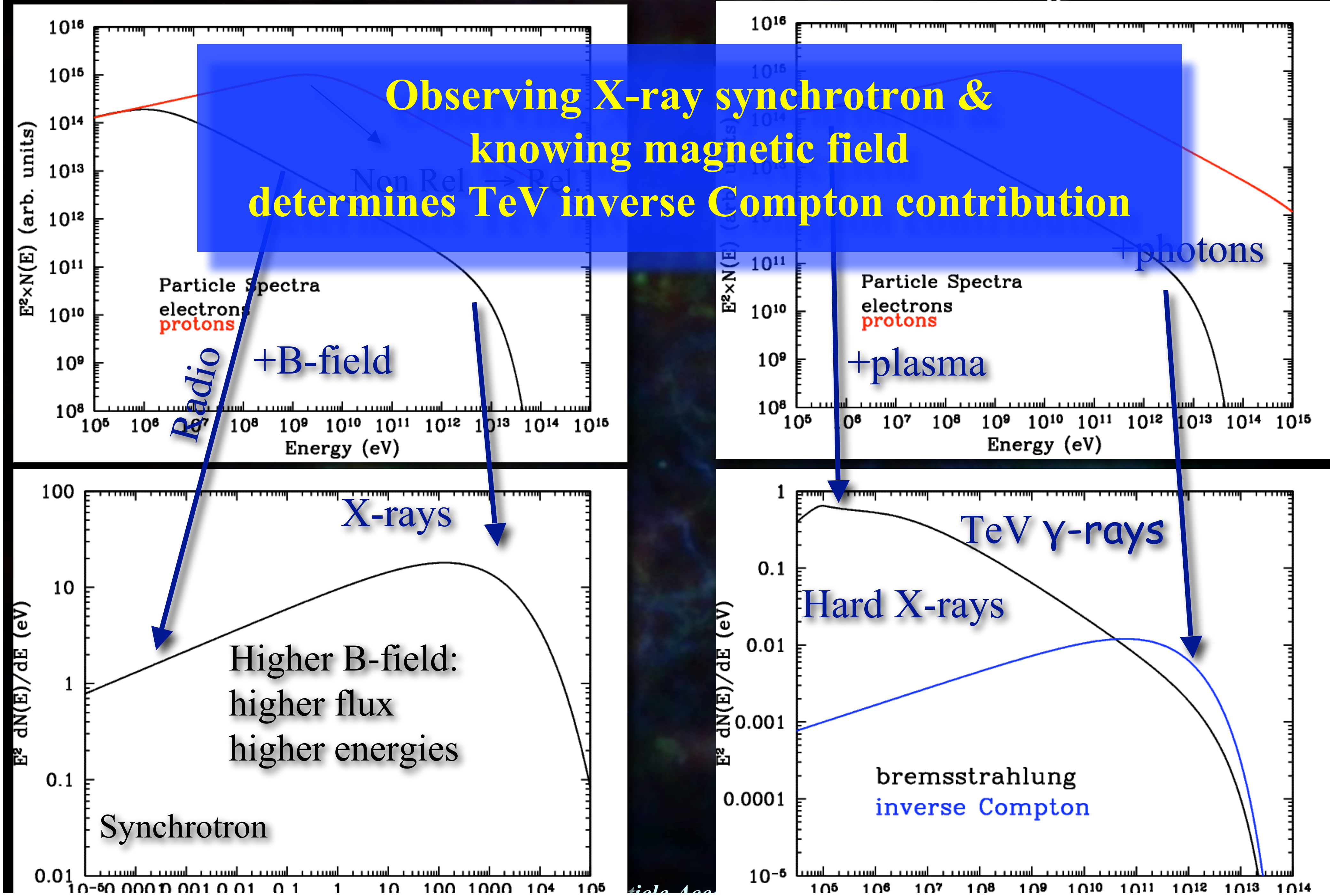
SN1006 (X-ray/Chandra)



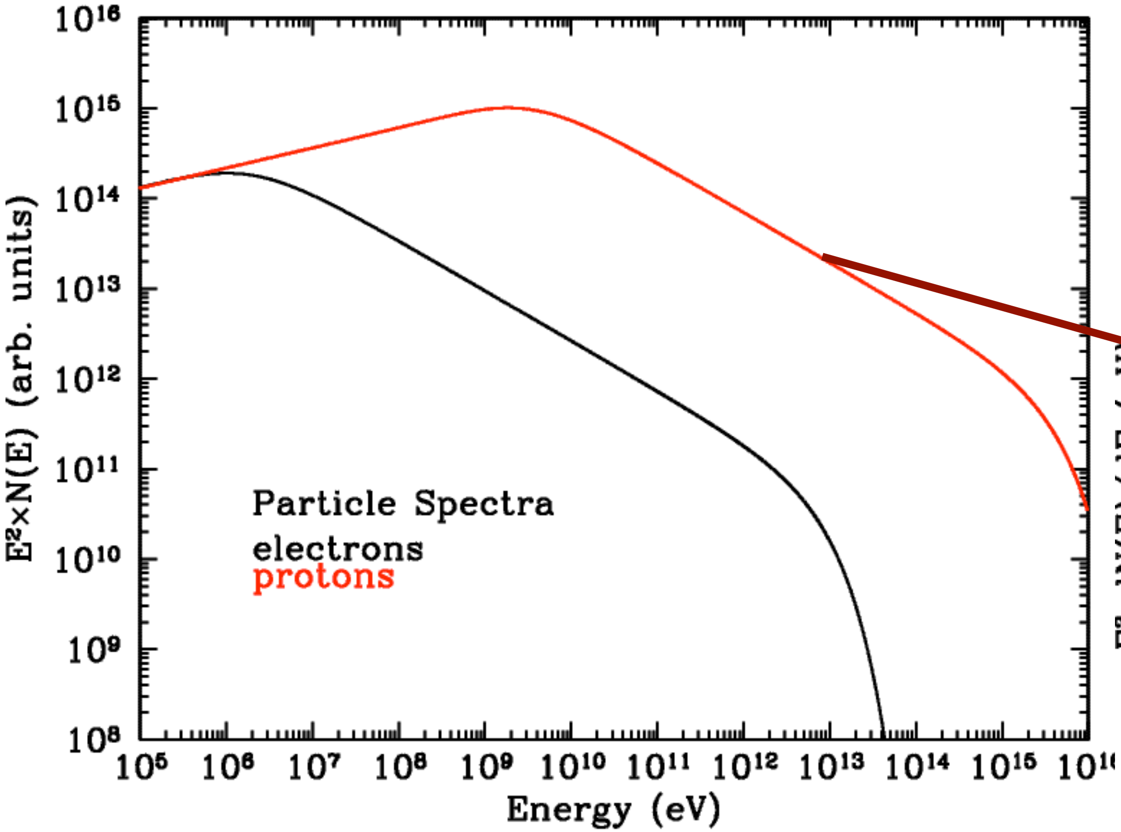
RX J1713... (HESS/TeV)

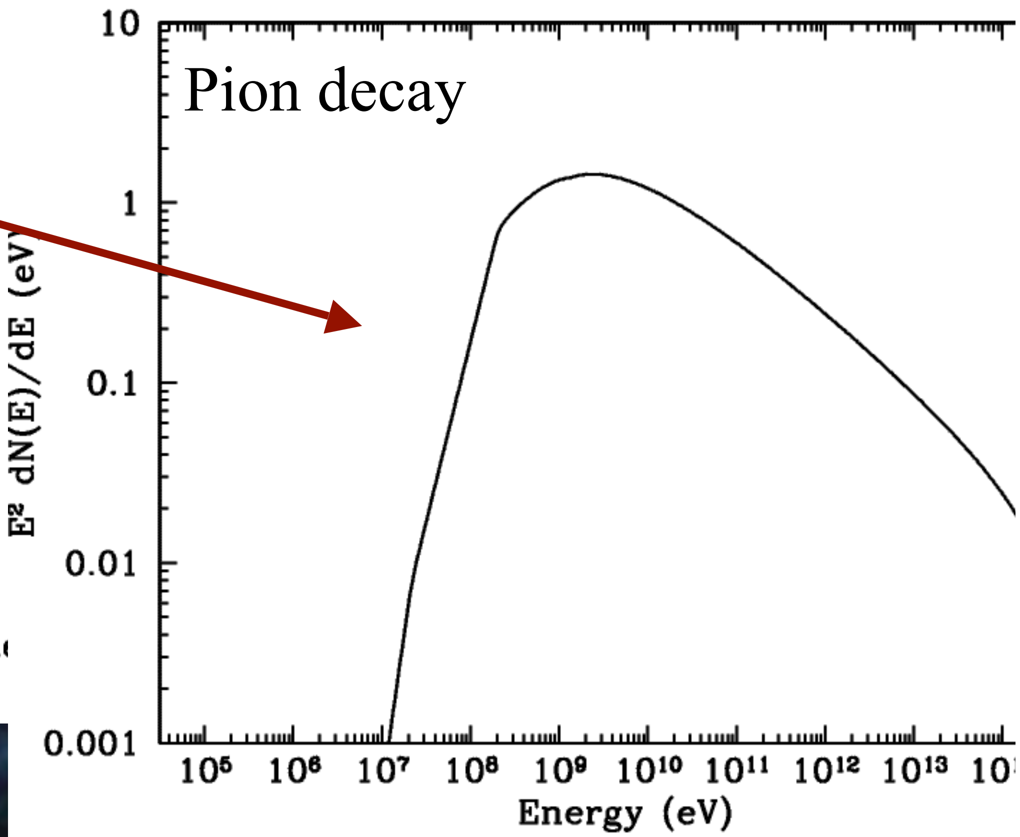
- Observed Cosmic Rays in SN Remnants: mostly electrons (leptons)
- Radio to X-rays: synchrotron emission
- TeV emission: 1. electrons: inverse Compton emission
  (G. Herman's talk) 2. ions (hadrons) through π^0 decay!
- This talk: X-rays

Radiation from Cosmic Rays



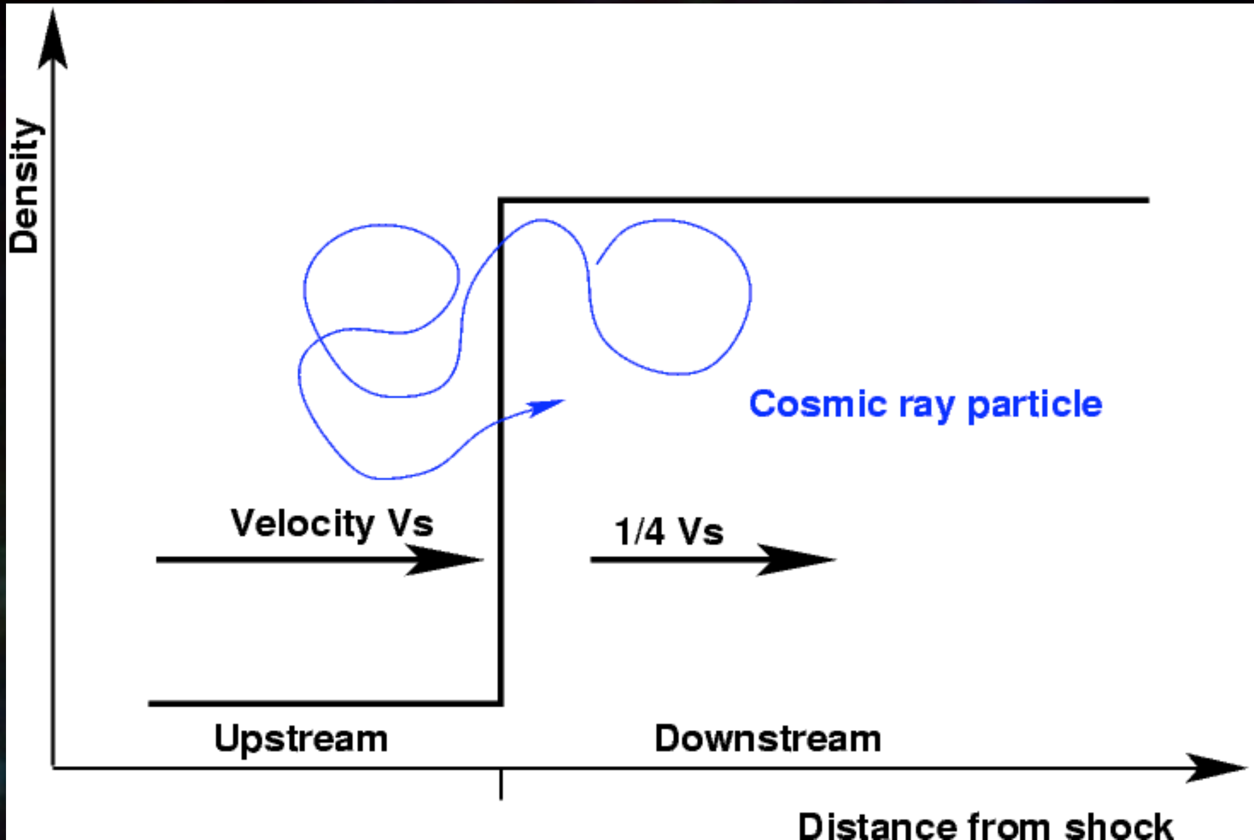
Radiation from Ions





- Energetic protons + background proton produce pions (π^0,π^+,π^-)
- Radiation: p+p $\rightarrow \pi^0 \rightarrow 2\gamma$ (bump in GeV to TeV range)
- Detecting pion decay $\rightarrow$ evidence for proton acceleration

Some acceleration physics



- Particles scatter elastically from downstream to upstream and vice versa
- Each shock crossing the particle increases its momentum with a fixed fraction ($\Delta p = \beta p$)
- Resulting spectrum (e.g. Bell 1978): $dN/dE = C\, E^{-(1+3/(X-1))}$ (X shock compression ratio, X=4 $\rightarrow$ $dN/dE = C\, E^{-2}$)

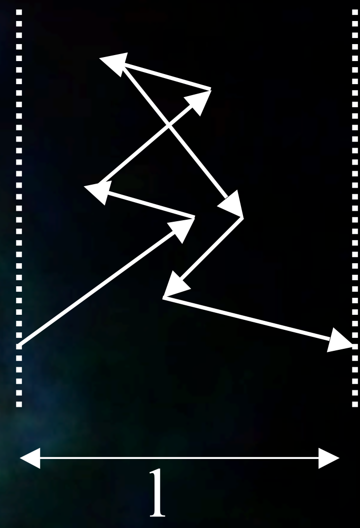
The diffusion length

How big is the region from which particles are accelerated?

Random walk: for a displacement of l the actual distance a particle travels is $\propto l^2$.

The average particle velocity is v (=c).

The mean free path is λ, the fluid velocity is u.



Time taken $\qquad T = 3\,(l/\lambda)\, l/v = 3\, l^2/\lambda v$

The fluid needs for this distance $\quad T = l/u$

For short distance diffusion works well,

for long distance advection works well.

The diffusion length scale is the boundary between the two:

$T_{adv} = T_{diff} \quad \rightarrow \quad l_{diff} = \lambda v/3u$

The diffusion coeficient is defined as $D = \lambda v/3 = \lambda c/3$

Acceleration time

l_{diff} gives the region from which particles are accelerated.
The average time particles spend there before crossing the shock is a measure for the acceleration time

$$\tau_{acc} \approx l_{diff}/u = (\lambda v/3u)/u = \lambda c/3u^2$$

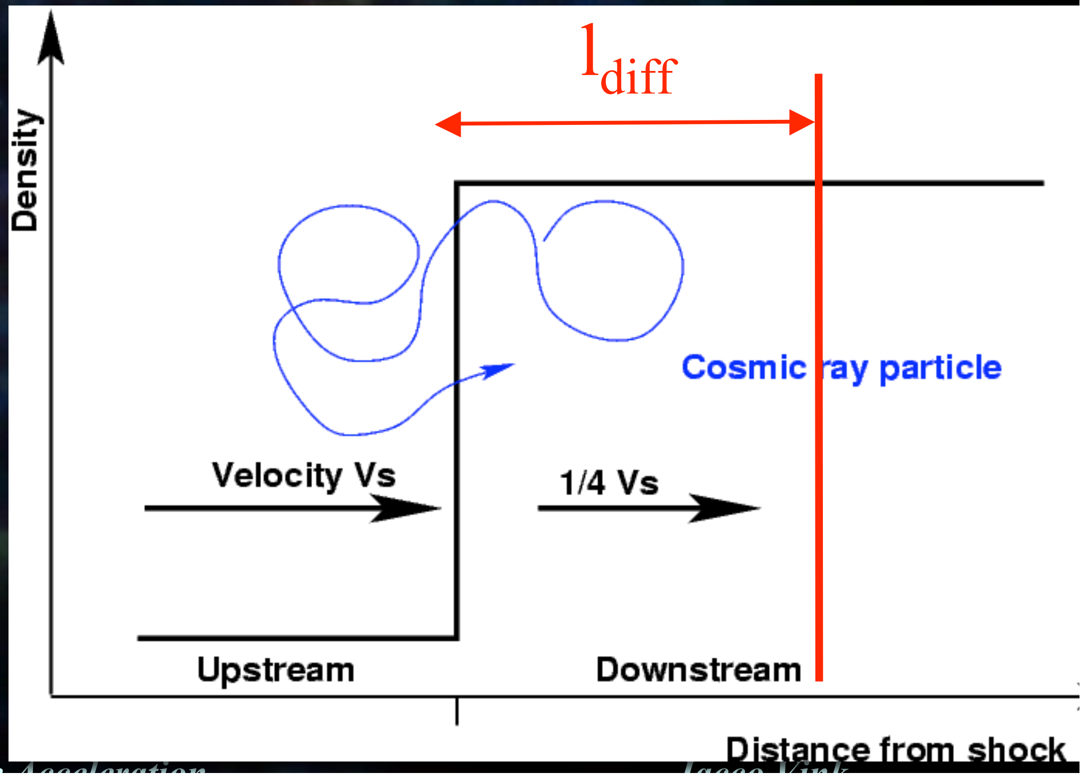
The particles scatter through magnetic field turbulence.
Thus the fastest acceleration/smallest λ implies λ = gyroradius

This defines the Bohm diffusion:

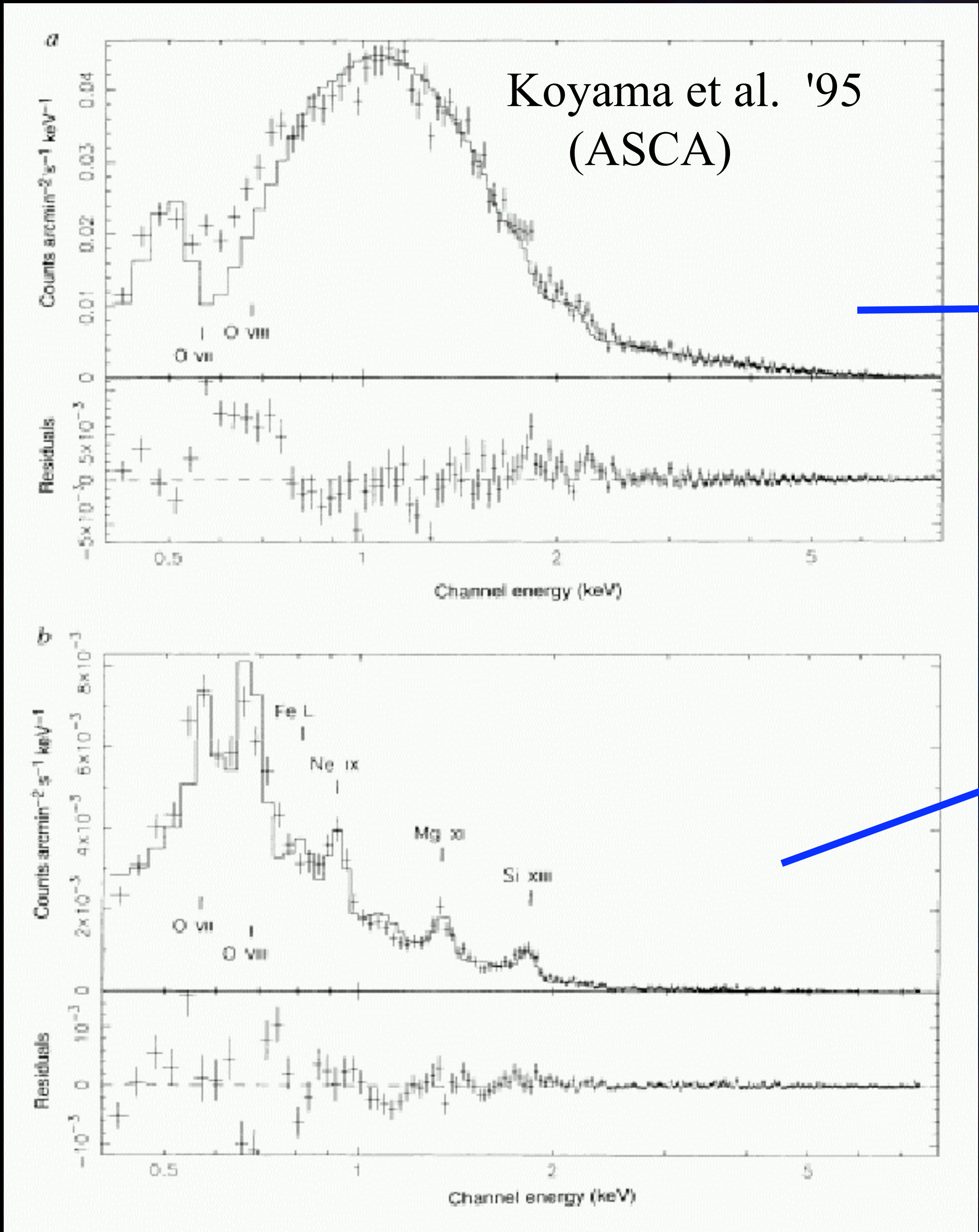
$$\lambda = E/eB$$

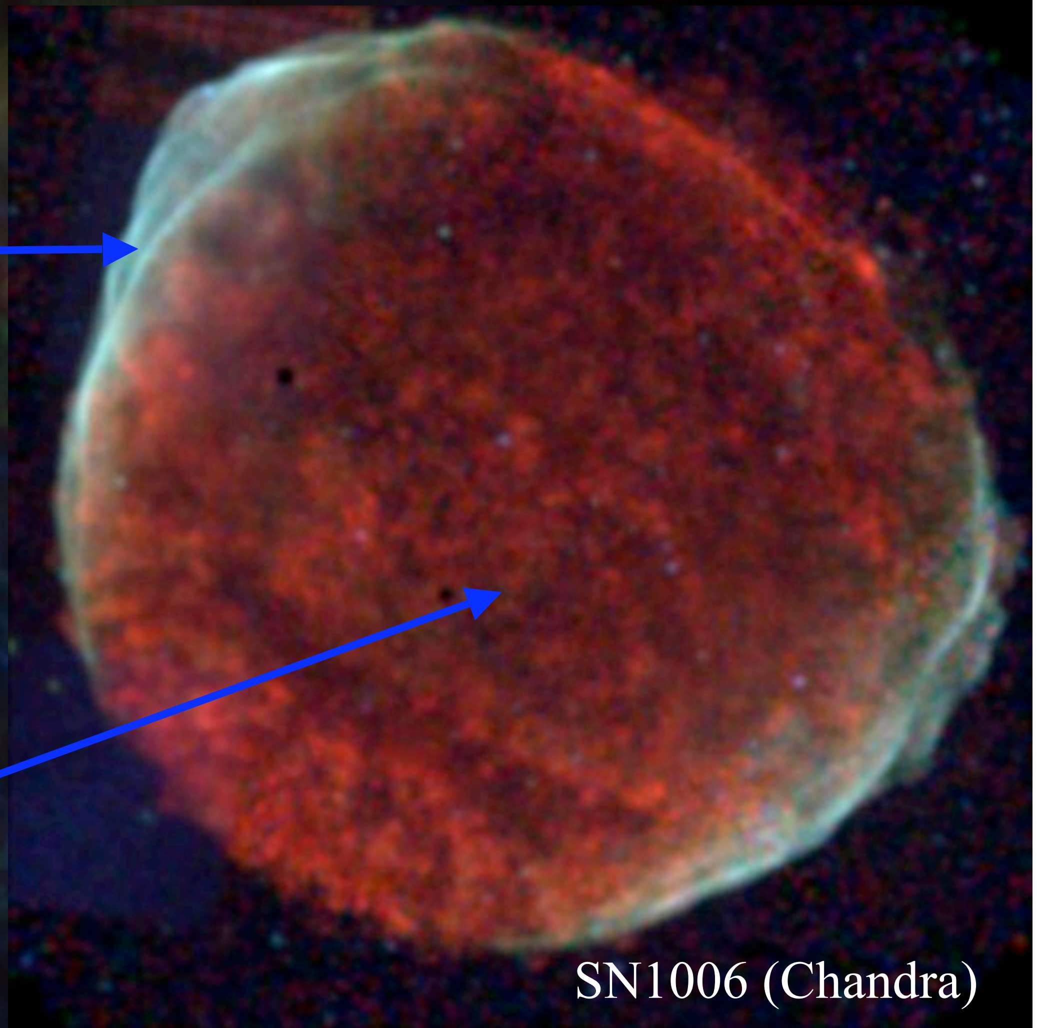
which means high turbulence:

$$\delta B/B \sim 1$$



First Evidence for efficient CR acceleration

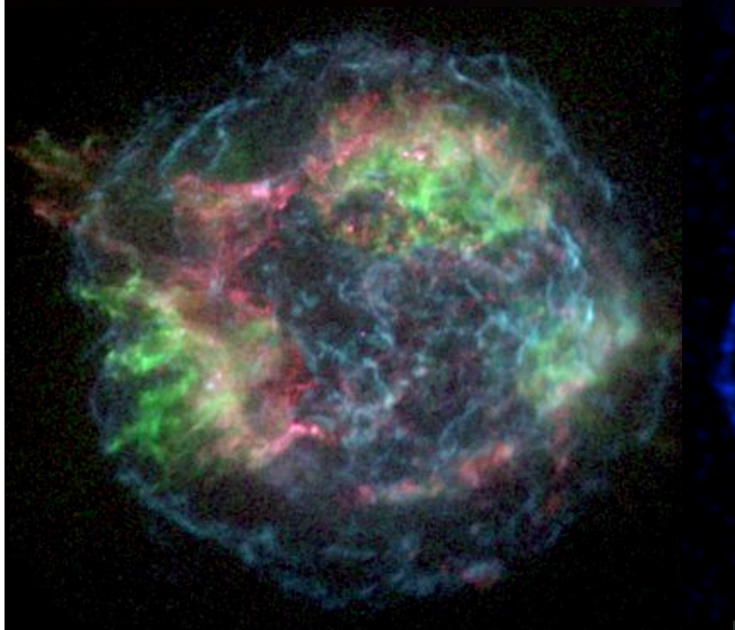


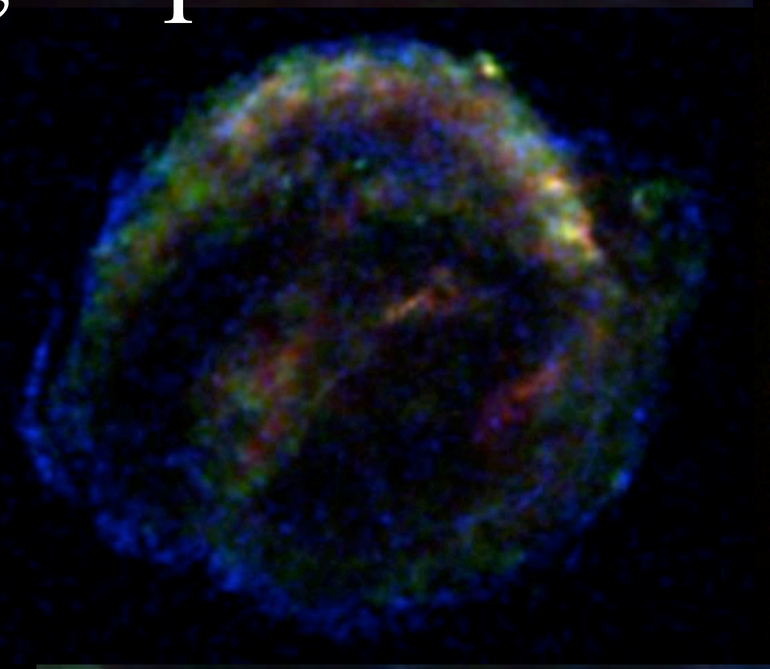


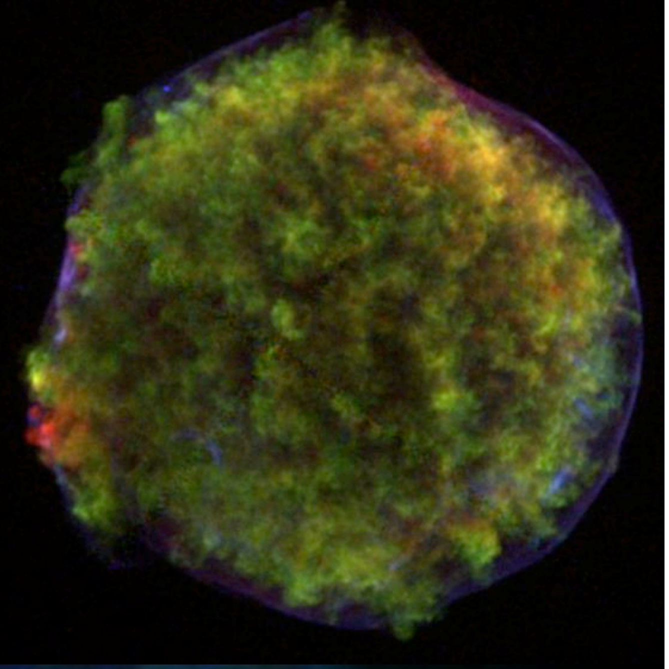
SN1006 (Chandra)

X-ray synchrotron radiation:
electrons up to ~5x10^{13} eV
(but depends on B-field)

Young Supernova Remnants







Cas A (SN1671?)

Kepler (SN1604)

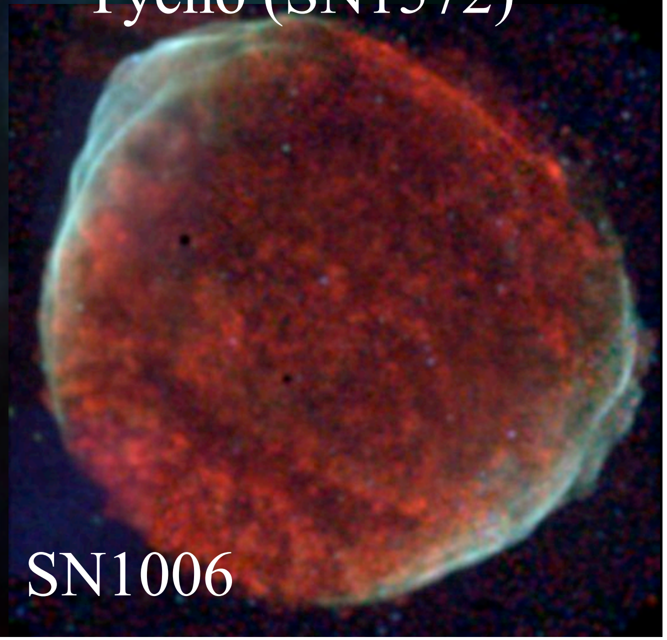
Tycho (SN1572)

(continuum emission in blue)

New developments:

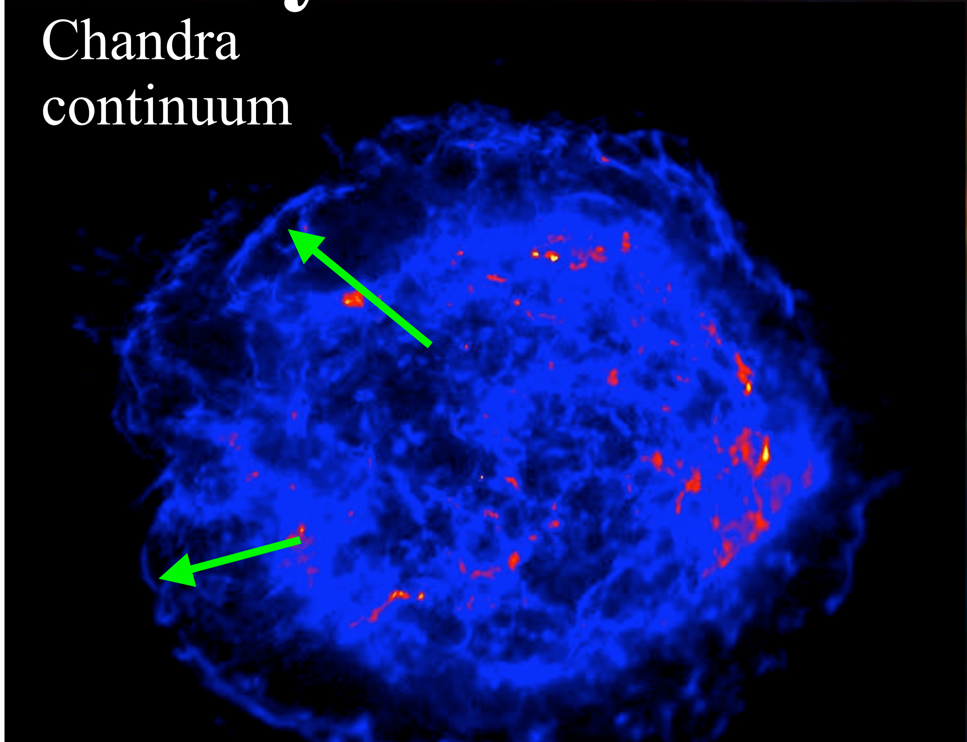
1 TeV detections of SNRs (→Aharonian)

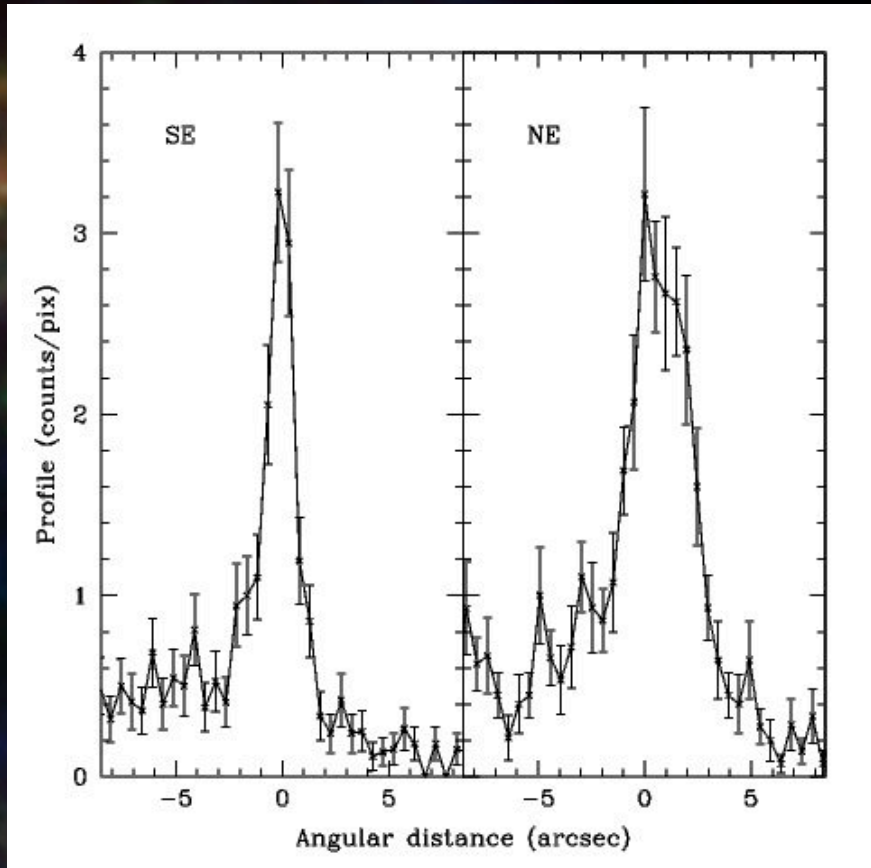
2 *All* young remnants emit X-ray synchrotron radiation from a narrow region near shock

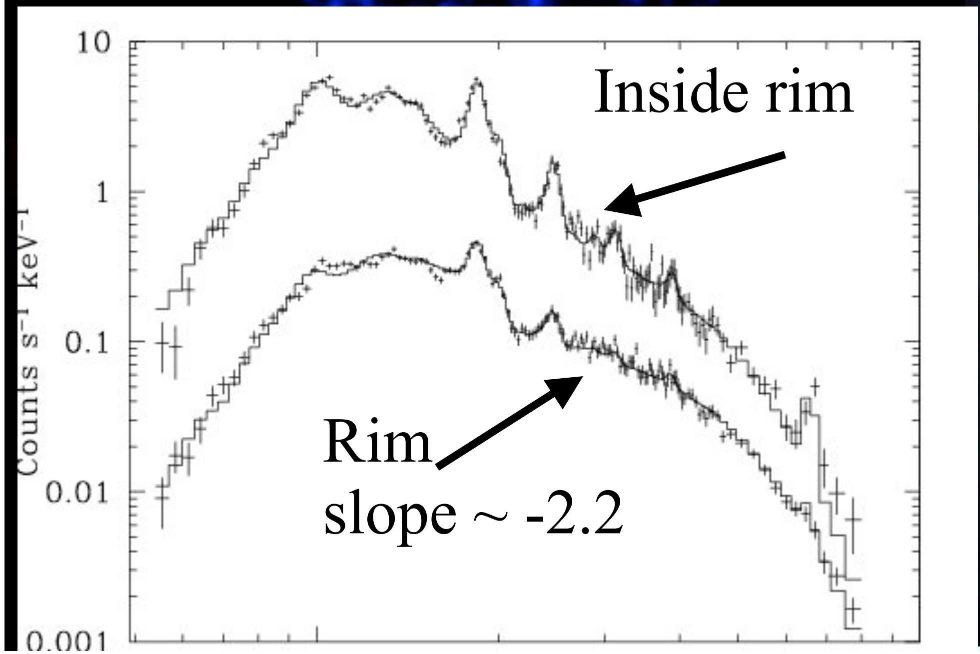


SN1006

Synchrotron rims of Cassiopeia A







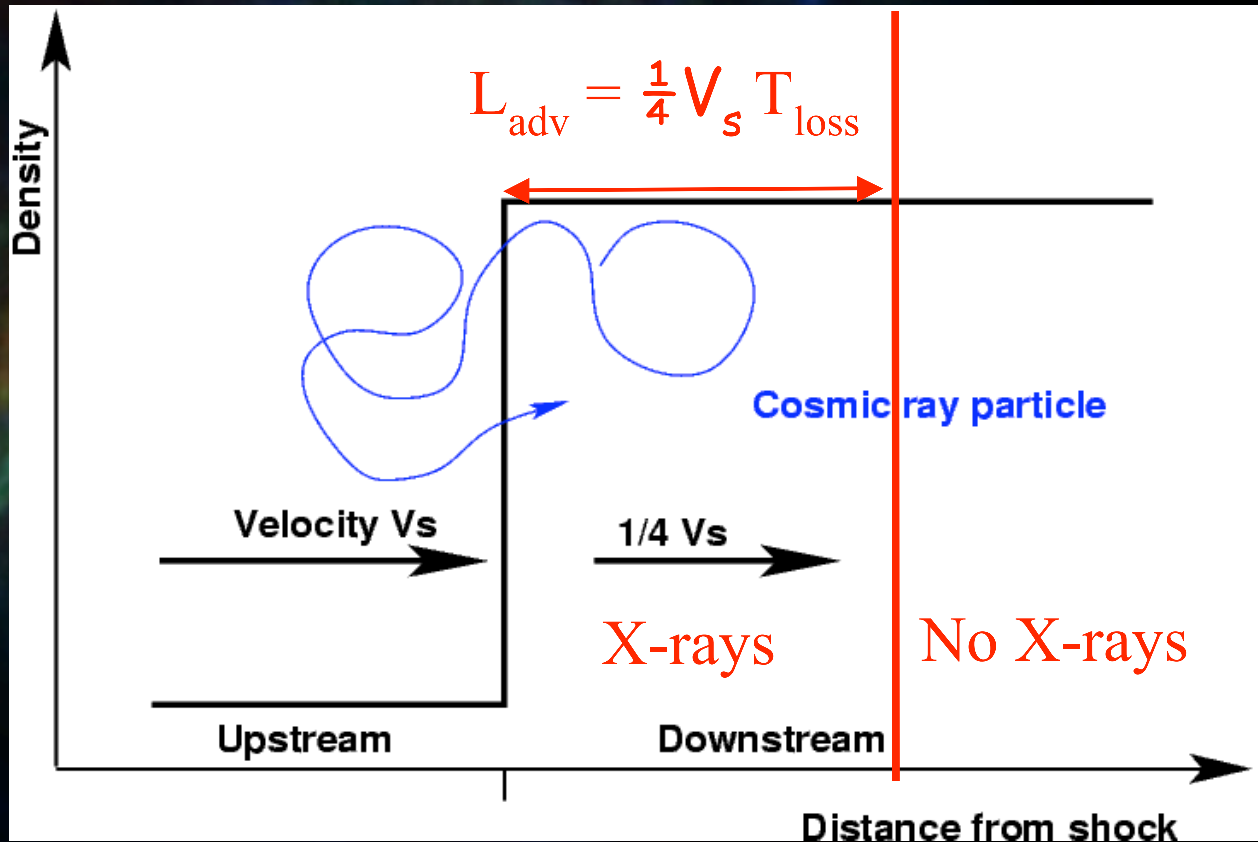
Rims are narrow and continuum dominated
1.5” to 4”
(0.025 – 0.07 pc)

(Vink & Laming 2003)

The Magnetic Field near the Shock

- Rim emission dominated by X-ray synchrotron radiation
- Rim width corresponds to synchrotron loss time, T, through $l_{adv} = \Delta V\ T$ (advection length)
- $V_s = 5200$ km/s (Vink et al. '98, Delaney et al. '03)
- $\Delta V = u = \frac{1}{4} V_s = 1300$ km/s (plasma velocity)
- Loss times 18 – 50 yr
- Loss time $T \sim 1/B^2 E$
- $E_{photon} \sim E^2 B$

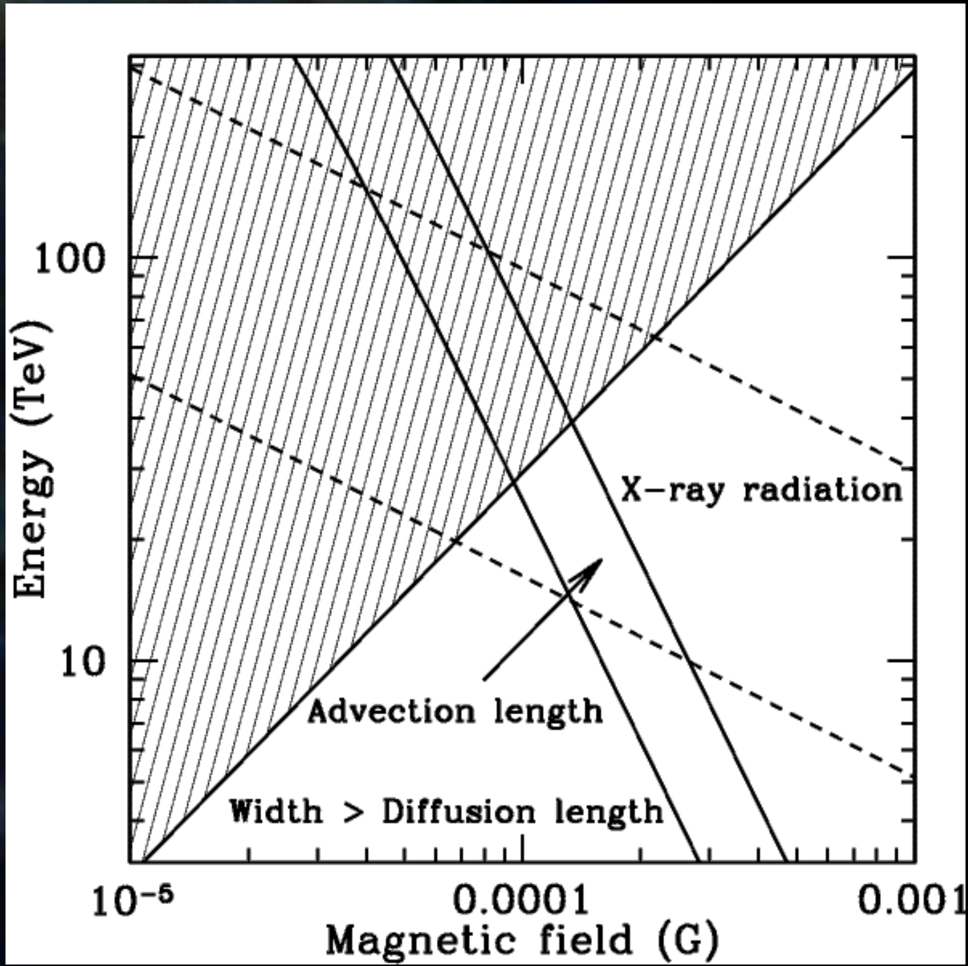
(Vink & Laming 2003)



Determining the Magnetic Field

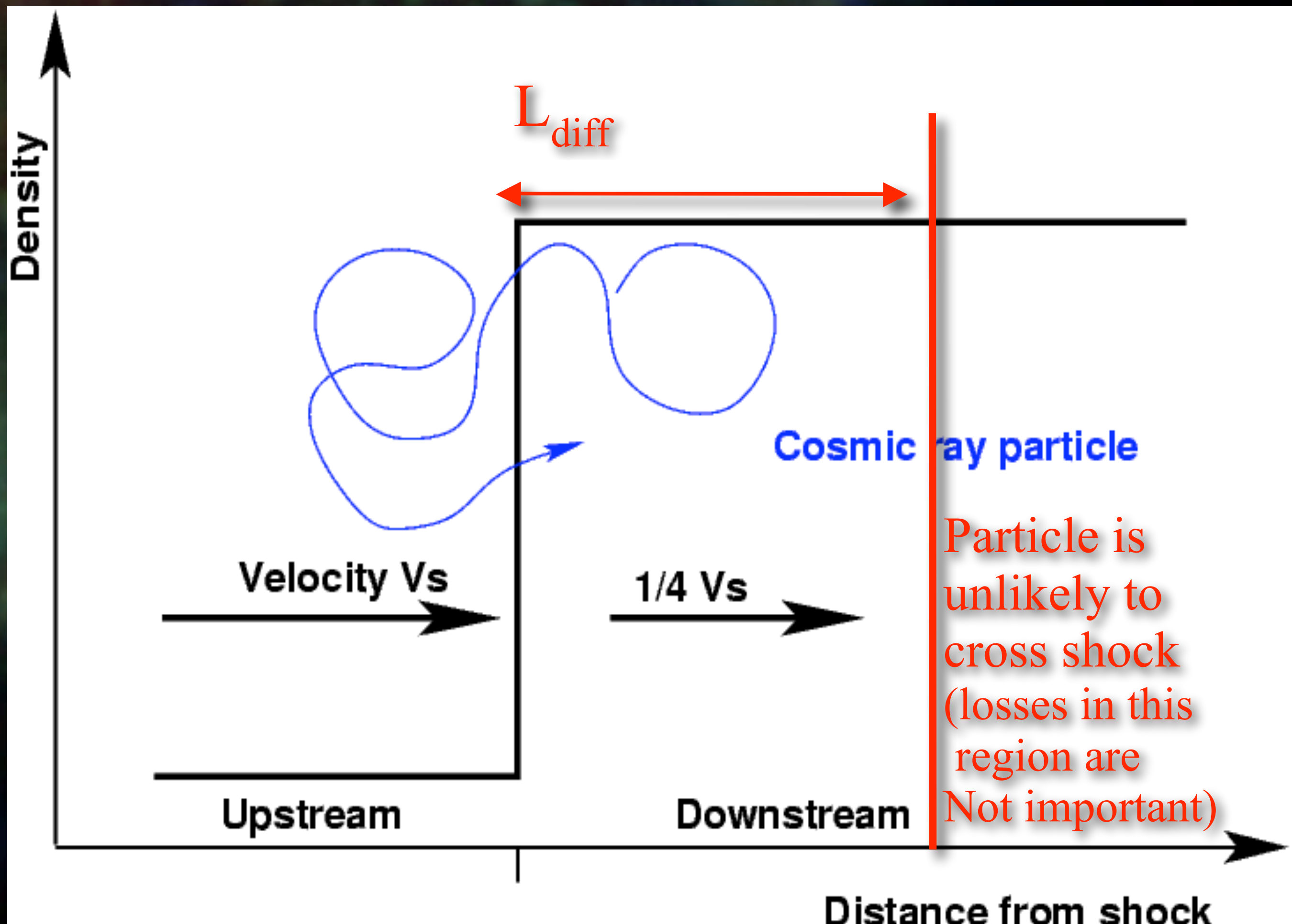
Combining gives:
B = 100 – 300 μG
downstream of shock!
(c.f. mean Galactic ~5 μG)

- Alternative:
  widths is set by diffusion length
  (Bamba et al. '04, for SN1006)
- $L_{diff} = D/u$
  - -D diffusion parameter,
  - - Bohm limit $D = cr_g/3 = Ec/3eB$
  - - Bohm limit most efficient acc. $(\delta B/B \sim 1)$
- Clearly always width $l_{obs} \geq l_{diff}$



Why diffusion & advection give same B-field

- For efficient acceleration: $L_{adv} \geq L_{diff}$
- In X-rays: $L_{adv} \approx L_{diff}$, i.e. we see electrons with E_{max}
- Hence: power laws steeper than in radio, as observed
- $L_{adv} \approx L_{diff}$, for *Bohm-limit* → Observational evidence for Bohm-limit



A more formal approach

- Assume loss limited electron spectrum
- I.e. only a net acceleration when $T_{acc} < T_{loss}$
- Losses mostly downstream (higher B): $l_{adv} = uT_{loss}$
- Shock acceleration theory: $T_{acc} \approx D/u^2$
  (within a factor ~2)
- So acceleration only for : $D/u^2 < l_{adv}/u$
- But diffusion length $l_{diff} = D/u \Rightarrow l_{diff} < l_{adv}$

Consequence
For a loss limited spectrum
(i.e. steepened)

$$l_{diff} \approx l_{adv}$$

$$\Rightarrow$$

$$l_{obs} \approx (l^2_{diff} + l^2_{adv})^{1/2} = 0.7\, l_{adv}$$

Summary for all young remnants

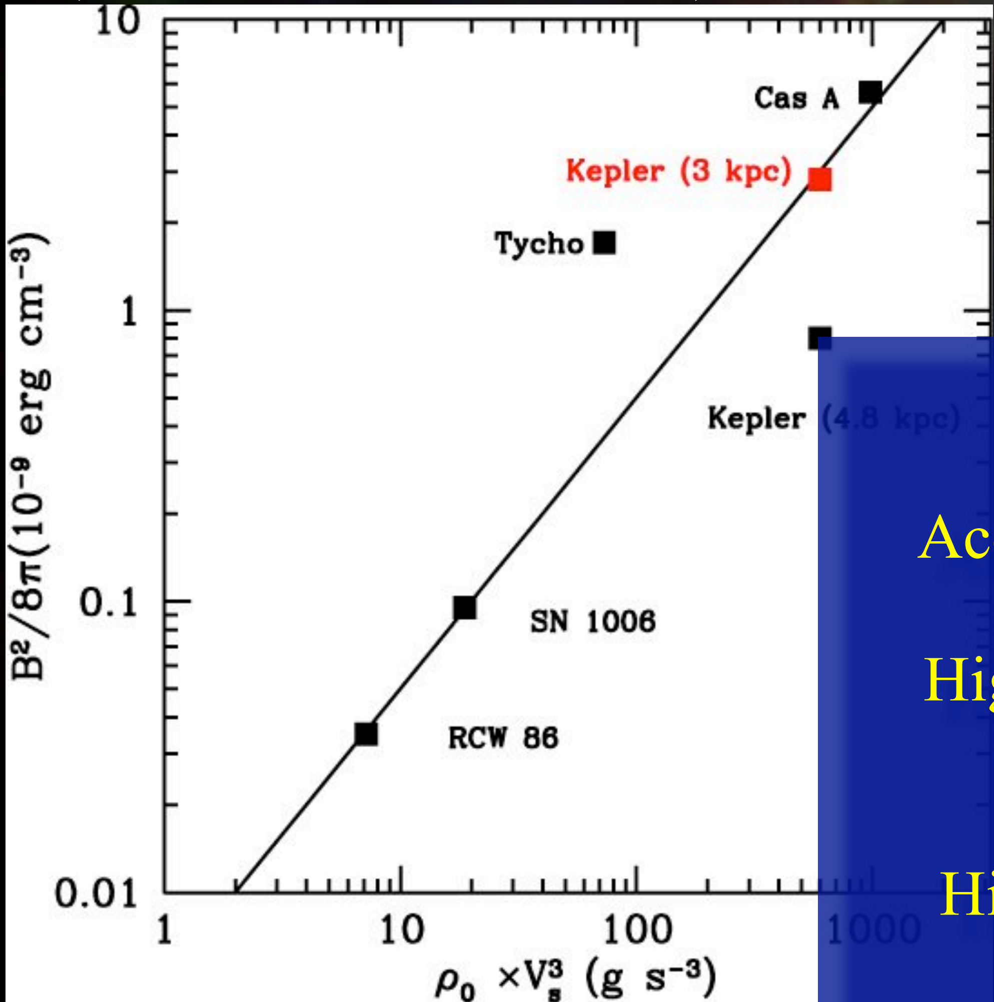
SNR	Age (yr)	Radius (')	V_s (km/s)	Width (")	B_{diff} (microG)	B_{loss} (microG)	$B_{combined}$ (microG)	P_B (dyne/cm^{-2})	P_{ram} (dyne/cm^{-2})	P_B/P_R X1000
Cas A	329	2.55	5189	0.5	298	249	376	2.5E-09	1.9E-06	1.3E+00
Kepler	396	1.64	5268	1.5	113	132	142	7.0E-10	2.3E-07	3.1E+00
Tycho	428	3.95	4482	2	165	156	208	9.6E-10	1.4E-07	6.8E+00
SN1006	994	14.37	4311	20	33	41	49	6.8E-11	4.3E-08	1.6E+00
RCW 86	1815	22.5	3533	45	20	19	30	1.5E-11	2.9E-08	5.0E-01

(see also Bamba et al. '05, Ballet '05, Voelk et al. 2005, Warren et al. '05)

1) All young SNRs have high B-fields
Likely cause: B-field enhancements by cosmic ray streaming (Bell & Lucek 2001, Bell 2004)
2) $B_{diff} \sim B_{loss}$: Evidence for Bohm-diffusion!
3) Need ions to generate B-field and B-turbulence
4) B-field/V of Cas A high enough to reach
$E = 1.5 \times 10^{15}$ Z eV

Magnetic Field Amplification

There is a clear correlation between ρ, V and B, in rough agreement with theoretical predictions (Bell 2004).
(See also Voelk et al. 2005)



NB large dynamic range in density not in V_s !

Young SNRs have high B-fields
→
Acceleration beyond the knee possible!
→
Highest B-field for dense environments & shock velocities
→
Highest CR energies early on in dense Red super giant winds
(less shock deceleration and $\rho \propto r^{-2}$)

The oldest X-ray synchrotron emitter?

RCW 86 (SN 185?)

Problem:

Max synchrotron energy

$$E_{max} \sim V_s^2$$

Independent of B!

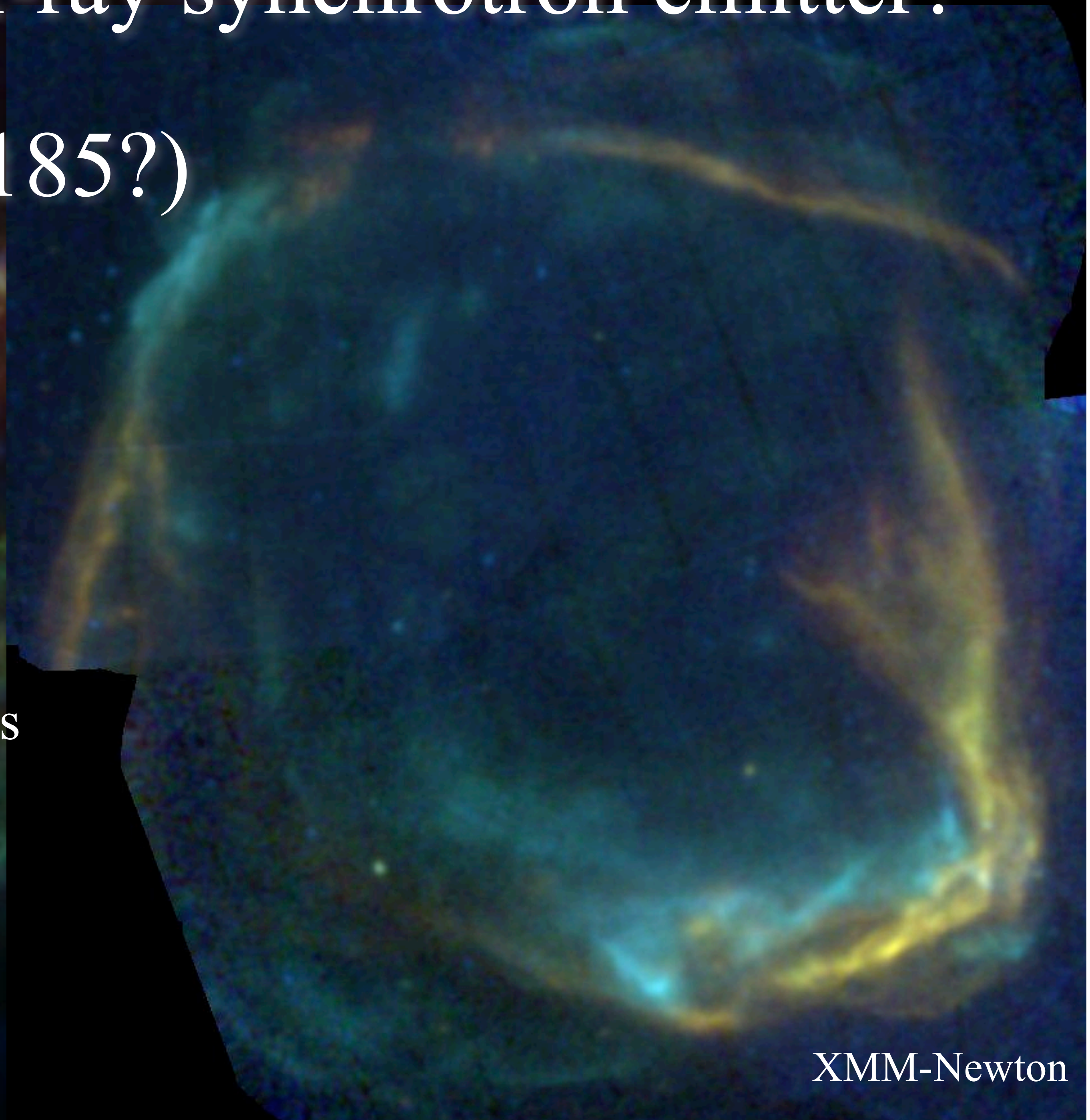
(Aharonian & Atoyan 2001)

But measured V_s~700 km/s

(Ghavamian et al. ‘01)

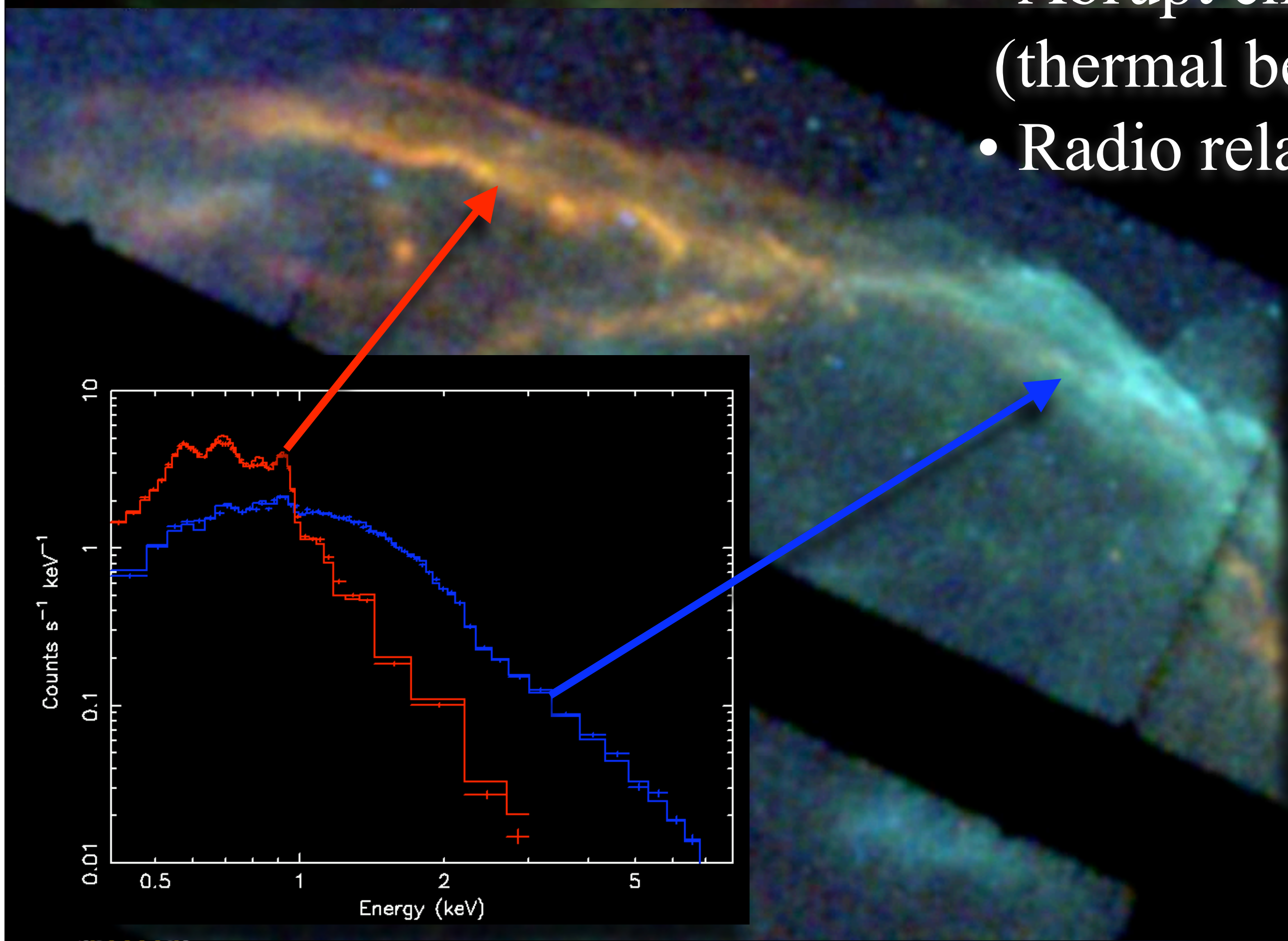
much lower than Cas A,

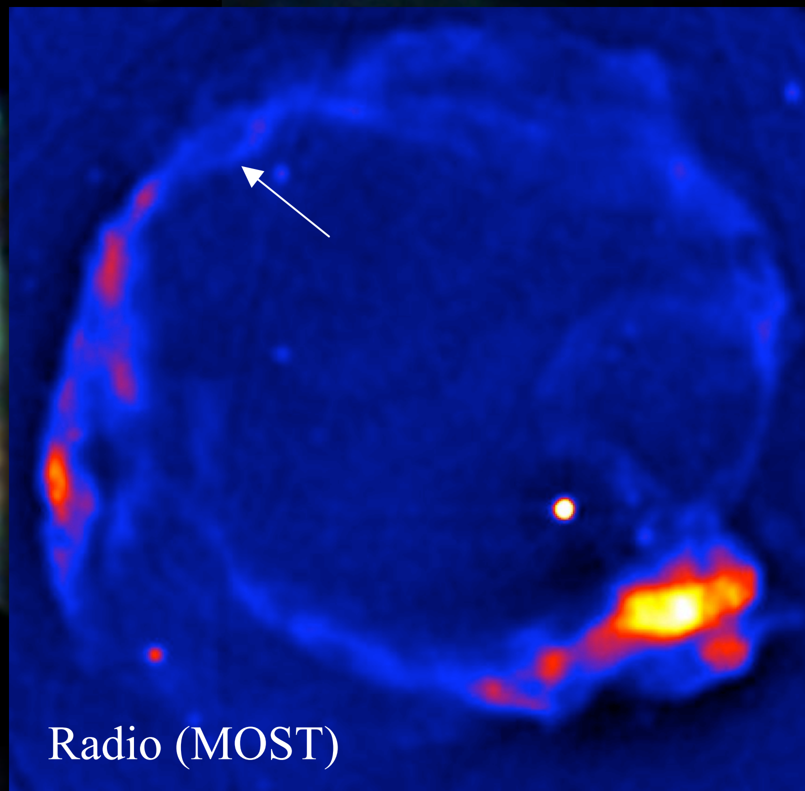
Tycho, SN1006 etc.



Chandra/XMM-Newton observations of Northeastern shell

- In NE synchrotron from shock front (edge on: 3D geometry less uncertain)
- Abrupt change thermal to non-thermal (thermal becomes weaker)
- Radio relatively weak





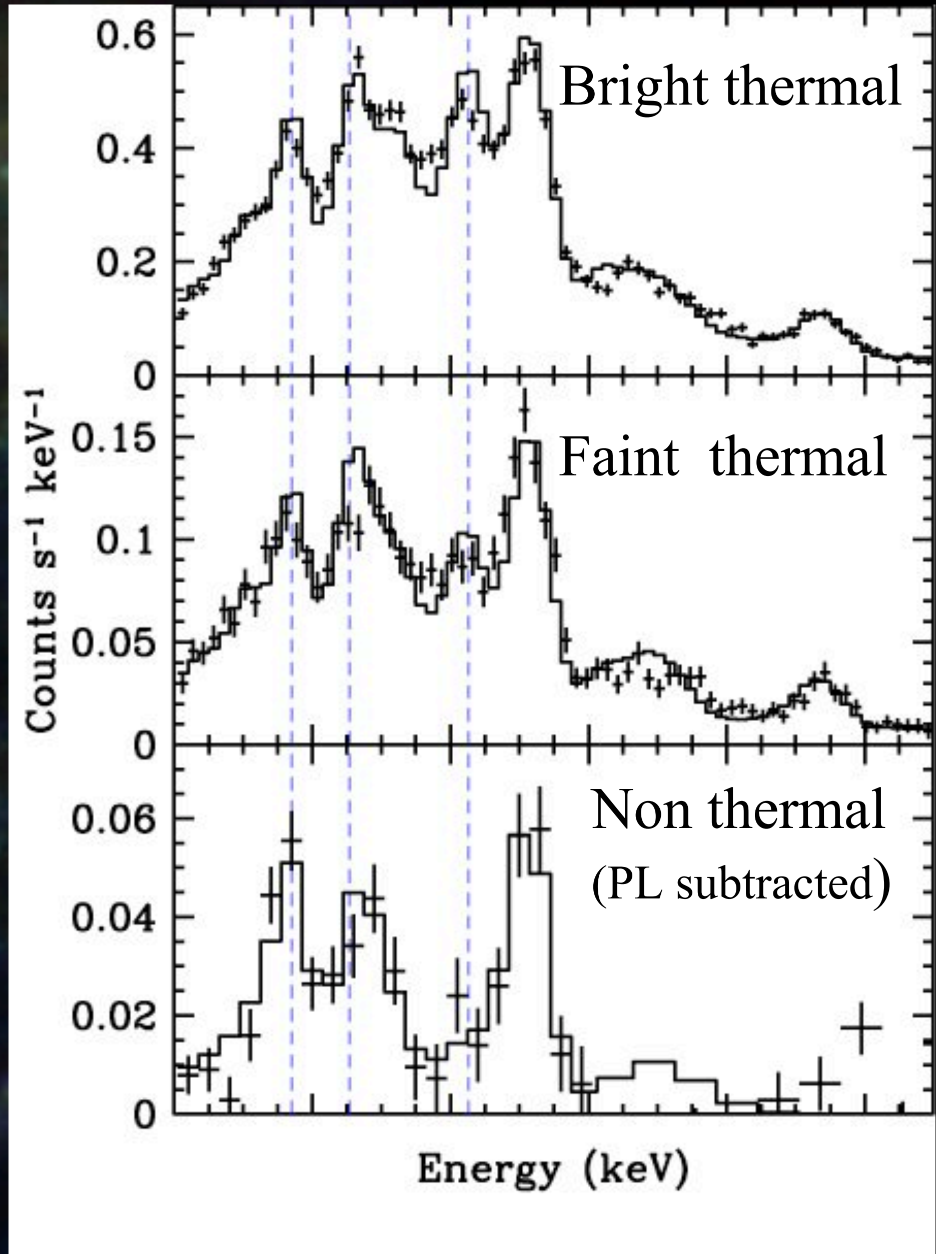
What are to make of this?

- From width (~45") and demanding diffusion and advection give same B-field (~20μG) we obtain Vs ~ 3000 km/s
- Much higher than Hα measurements (~700 km/s Ghavamian et al.), but consistent with shock theory
- Requires large differences in V_s along shell
- Consistent with shock partially interacting with cavity wall
- High shock velocity is consistent with identification RCW86=SN185!!
- Suggests also why new X-ray synchrotron/TeV remnants are large and faint (Ueno PhD Thesis 2005):
  low density → V_s remains high for longer time

weakness of radio:
not more electrons are accelerated
they are accelerated to higher energies!

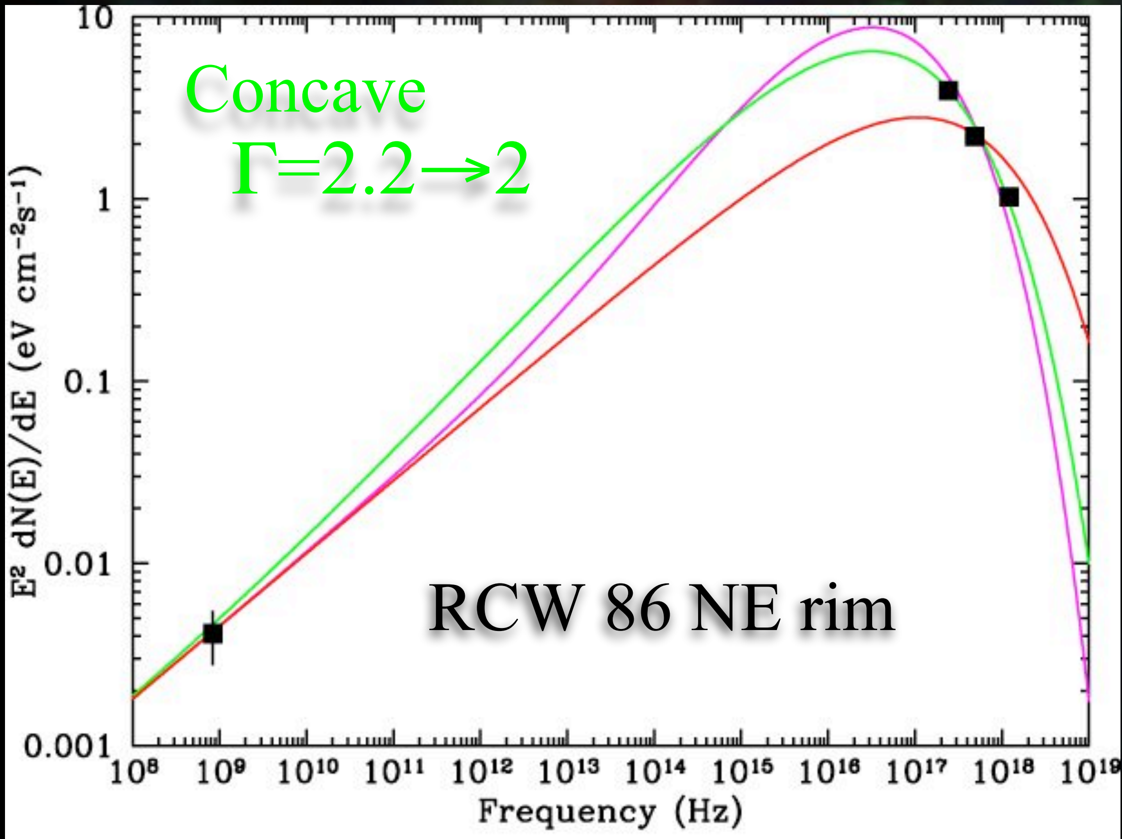
Thermal spectra

- Use thermal spectra to estimate time since interacting with cavity wall
- NE bright shell gives kT ~ 1 keV, $n_e t = 4 \times 10^9 \text{cm}^{-3}\text{s}$ (=ionization time)
- Emission measure: $n_e \sim 0.5\ \text{cm}^{-3}$
- Combining gives t ~ 250 yr
- So $\Delta R \sim \Delta V_s\, t = 0.8$ pc
  $\Delta R / R \sim 5\%$
  consistent with morphology!



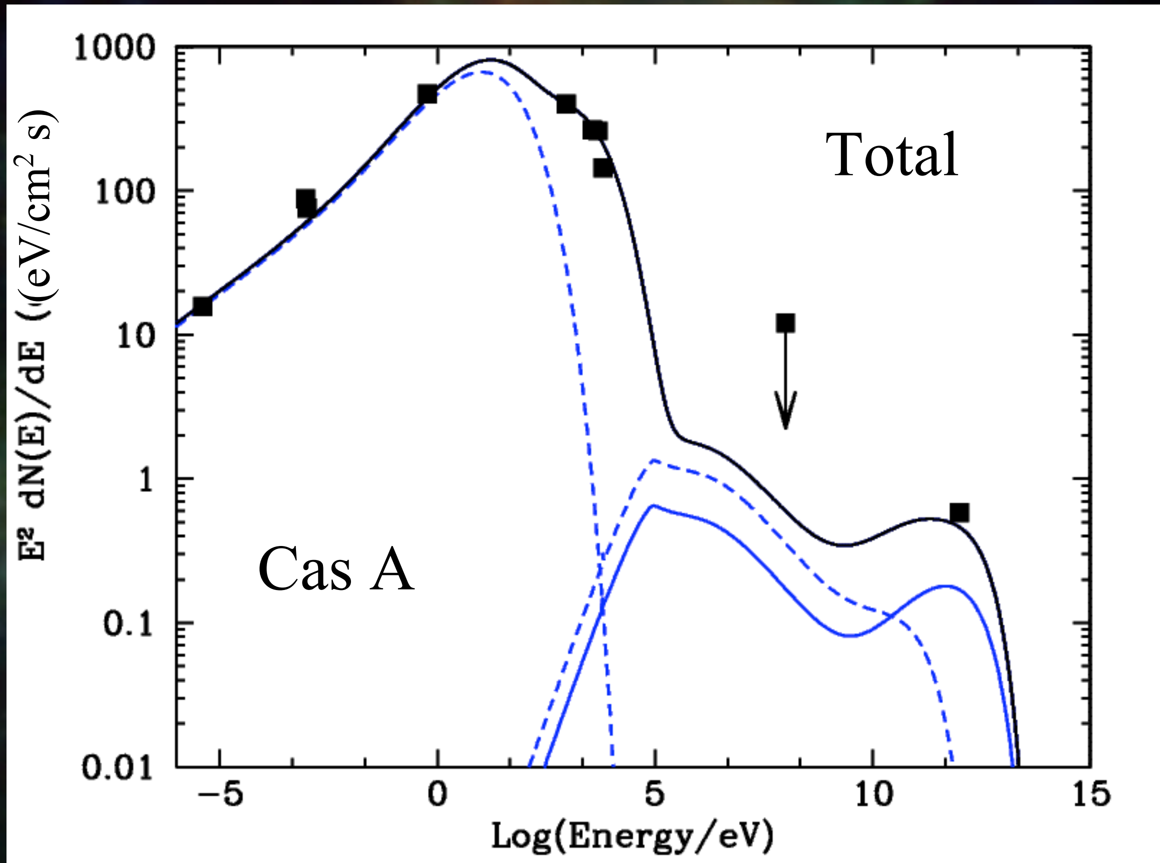
Radio vs X-ray synchrotron emission

How does weak radio emission fit in with X-ray synchrotron?



- Simple extrapolation of radio spectrum (srcut-like) does not fit
- X-ray index too steep!
- Requires flattening of spectrum to Γ=1.5 - 2
- Low maximum energy (e.g. ~8 TeV vs ~28 TeV)
- Flattening predicted for efficient cosmic ray acceleration (non-linear effects)

Concave spectra also fit Cas A better



Drawback: less need for pion decay TeV emission!!

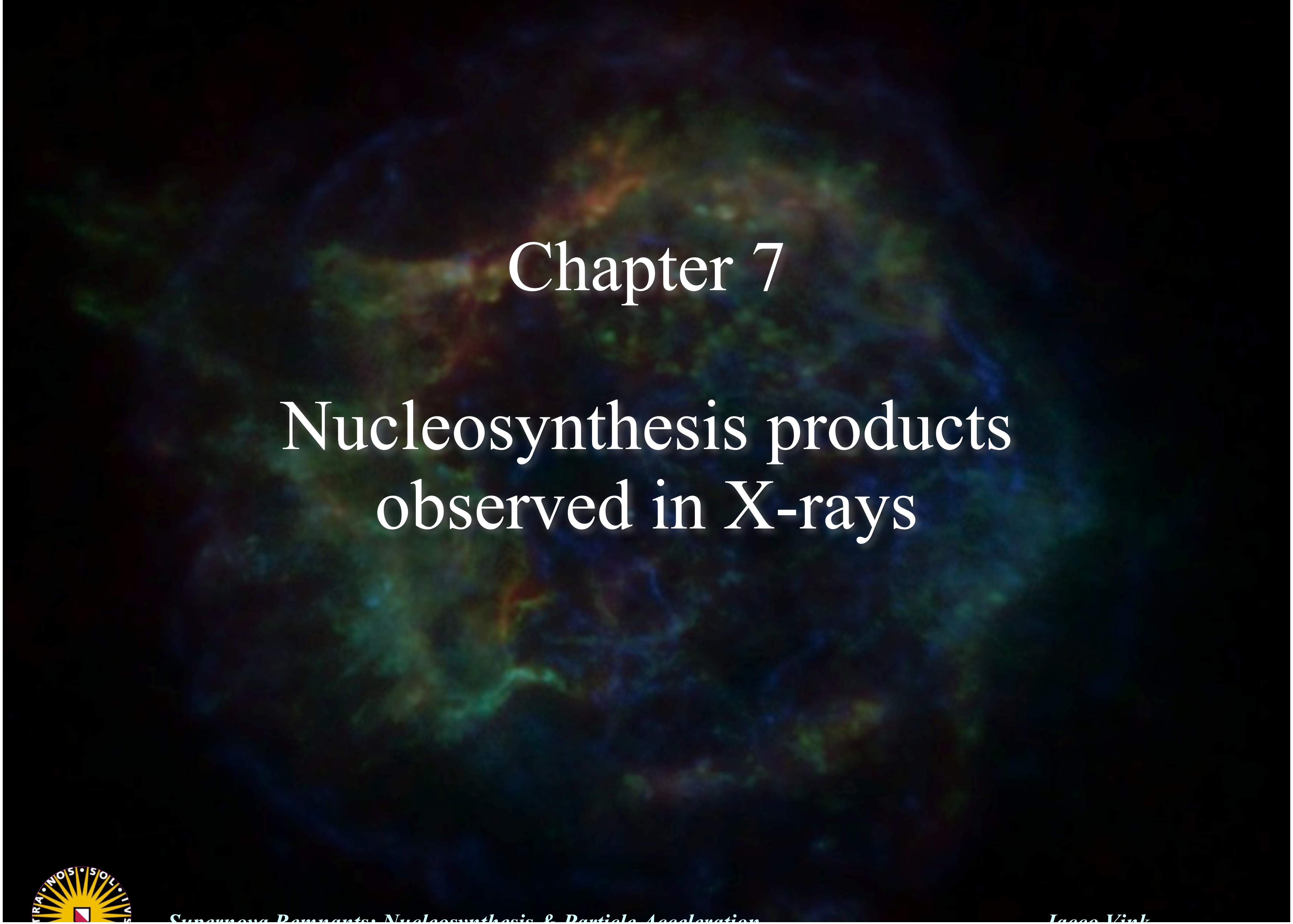
Uncertainties...

1 X-ray rim interpretation very consistent
diffusion vs advection, support for Bohm diffusion
But…
Assumption compression ratio = 4
Hydrodynamic models of Tycho give evidence for higher compression ratios

2 What is the correct interpretation of Cas A interior X-ray synchrotron filaments

Summary

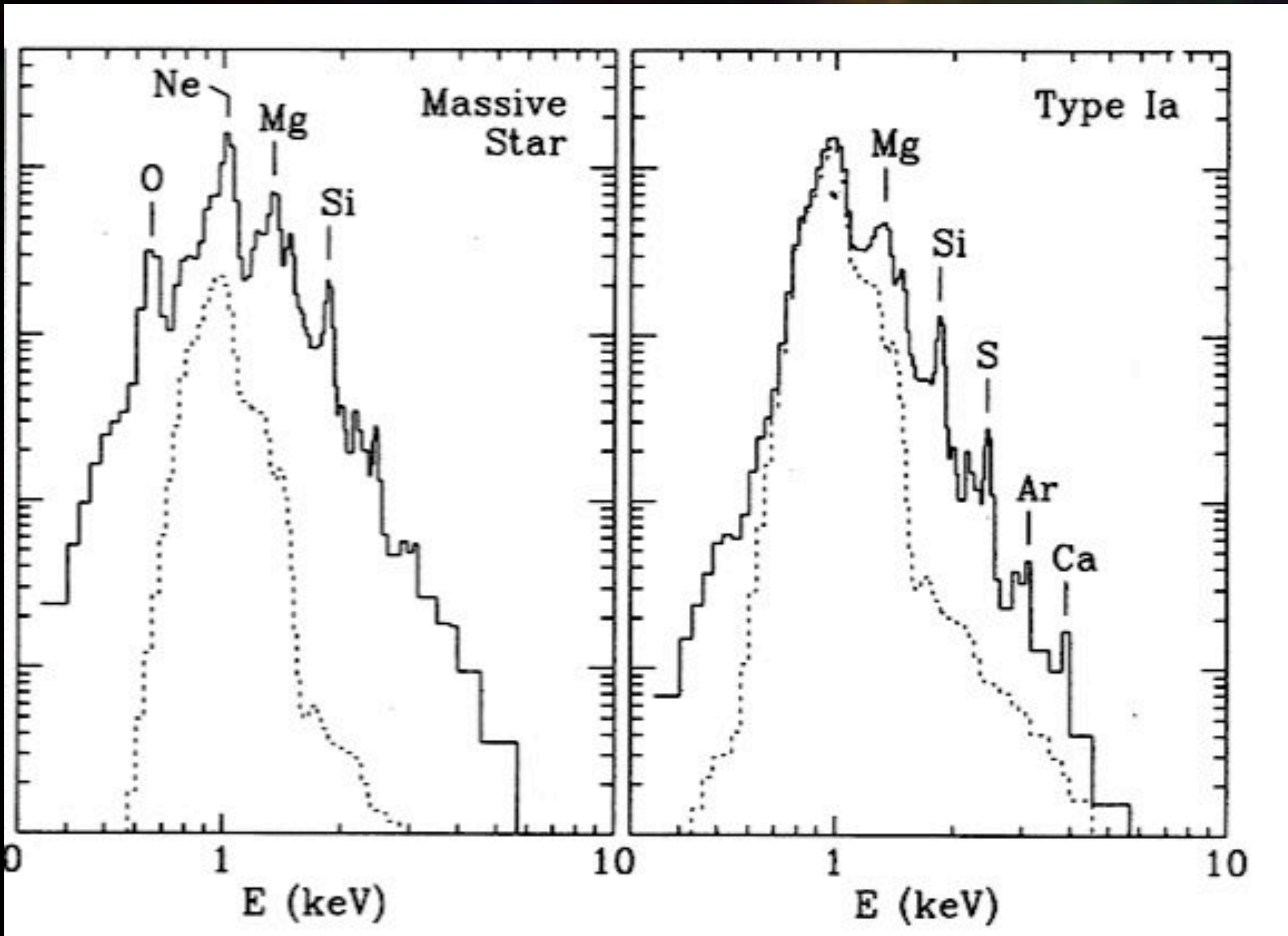
- All young SNRs show evidence for X-ray synchrotron emission
- These sources are good TeV candidates or have been detected in TeV
- Size of X-ray synchrotron region can be used the infer B
- Advection/Diffusion model requires Bohm diffusion
- B-field scales with density x V^{α}
- Loose ends: - rim width model vs Tycho hydro model
  - interior X-ray synchrotron Cas A



Chapter 7

Nucleosynthesis products observed in X-rays

Typing SNe from their SNRs



Synthethic spectra

Hughes et al. 1995

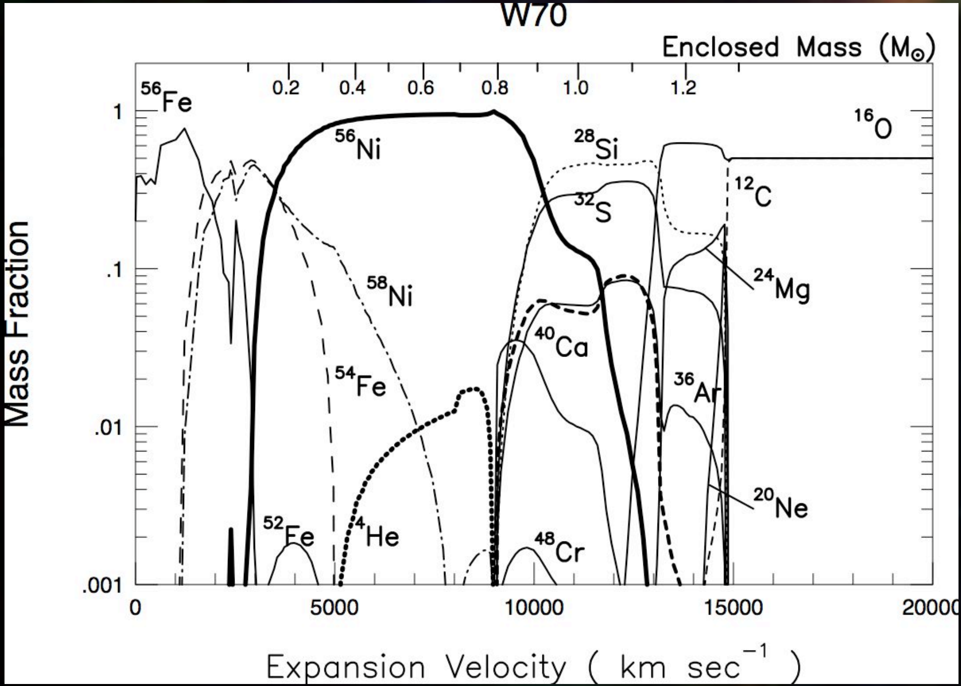
Different element expected for different SN types
Type II/Ibc: O/Ne/Mg rich, Type Ia Fe rich

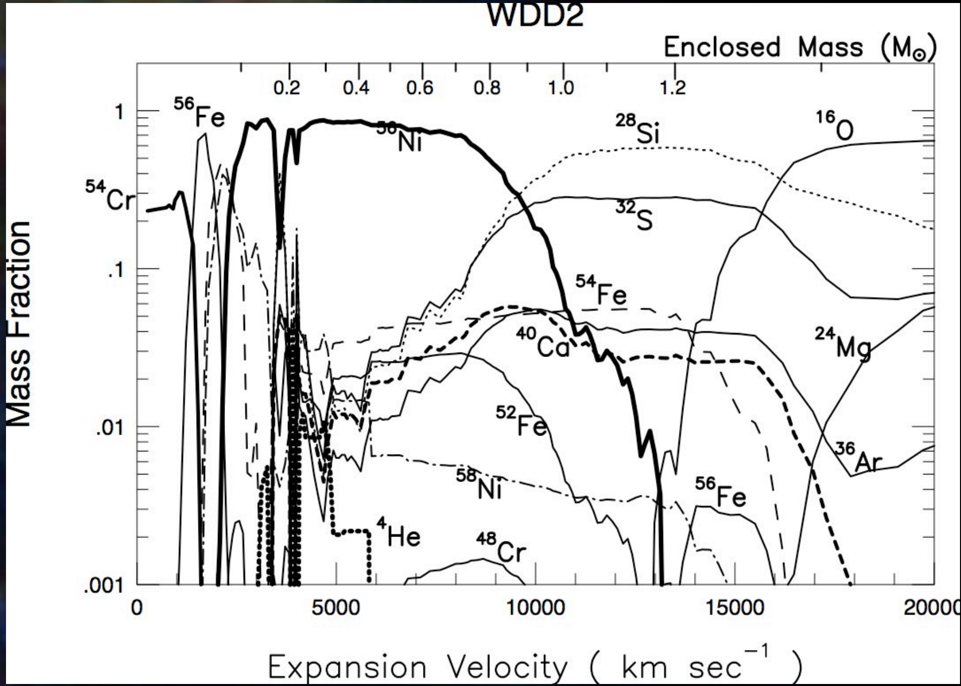
The Explosion Mechanism of Type Ia

All observations point to thermonuclear explosion of a C/O white dwarf, but many explosion models possible:

- Binary with one WD, or two WD merging? (double degenerate)
- How does the explosion start, from outside or inside?
- Explosion type:
  1. Detonation: i.e. shock wave moves through WD
     Not favored: almost all C/O burned into ^{56}Ni
  2. Deflagration: a subsonic flame, turbulence needed for mixing
     Famous model: W7 (Nomoto et al. ‘84)
     Works well for optical spectra (abundances) not for velocities
  3. Delayed detonation: currently favored
     A deflagration changes into a detonation

Nucleosynthesis yields of Type Ia SNe

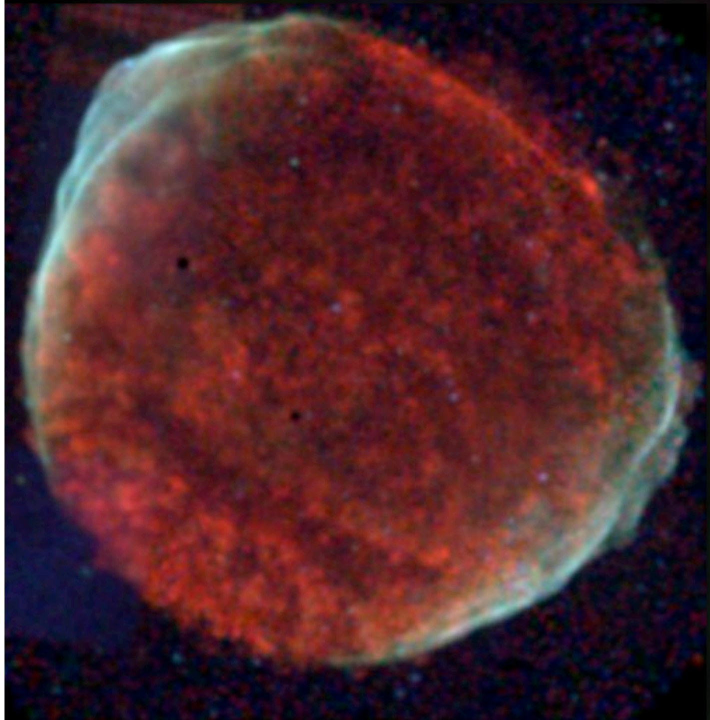




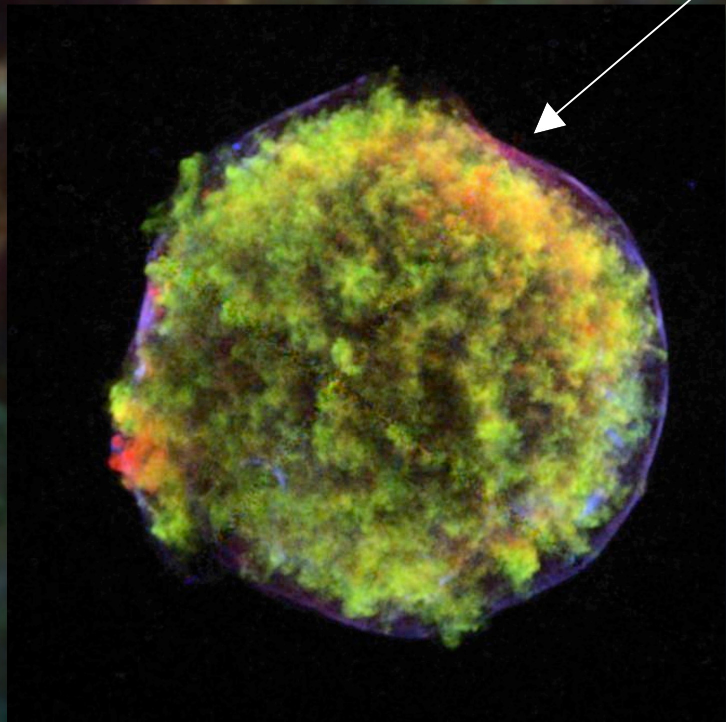
Deflagration/delayed detonation models
(Nomoto et al. '97)

Type Ia SNRs

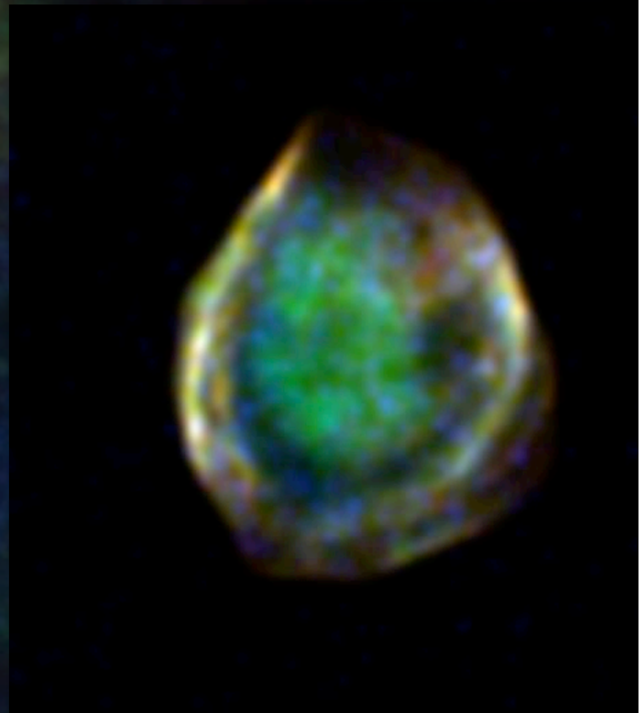
Daria Kosenko's talk



SN1006



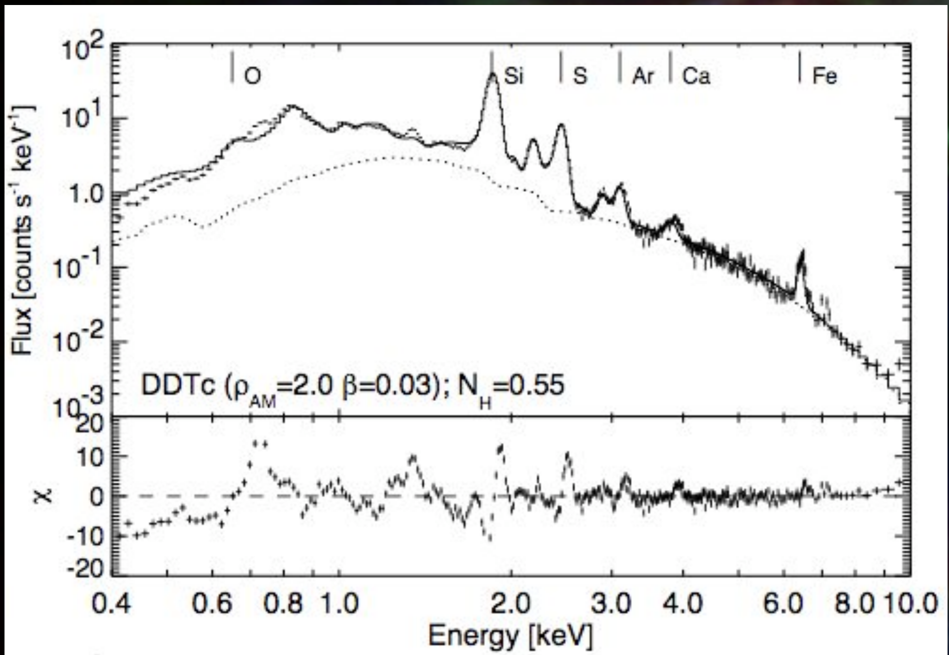
SN1572/Tycho

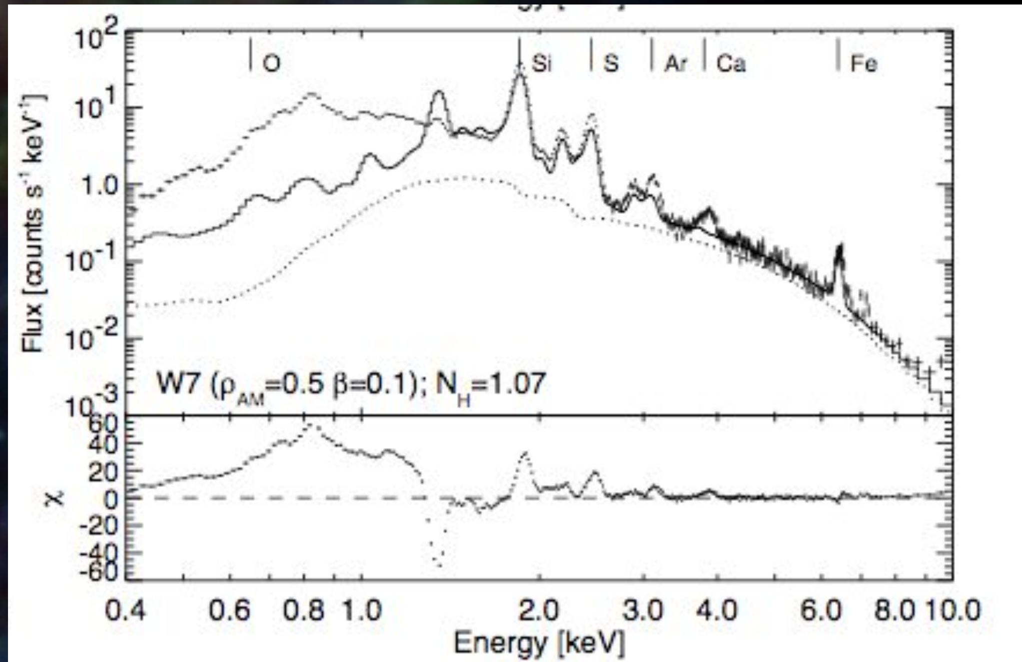


Dem L71

Advanced evolutionary stage

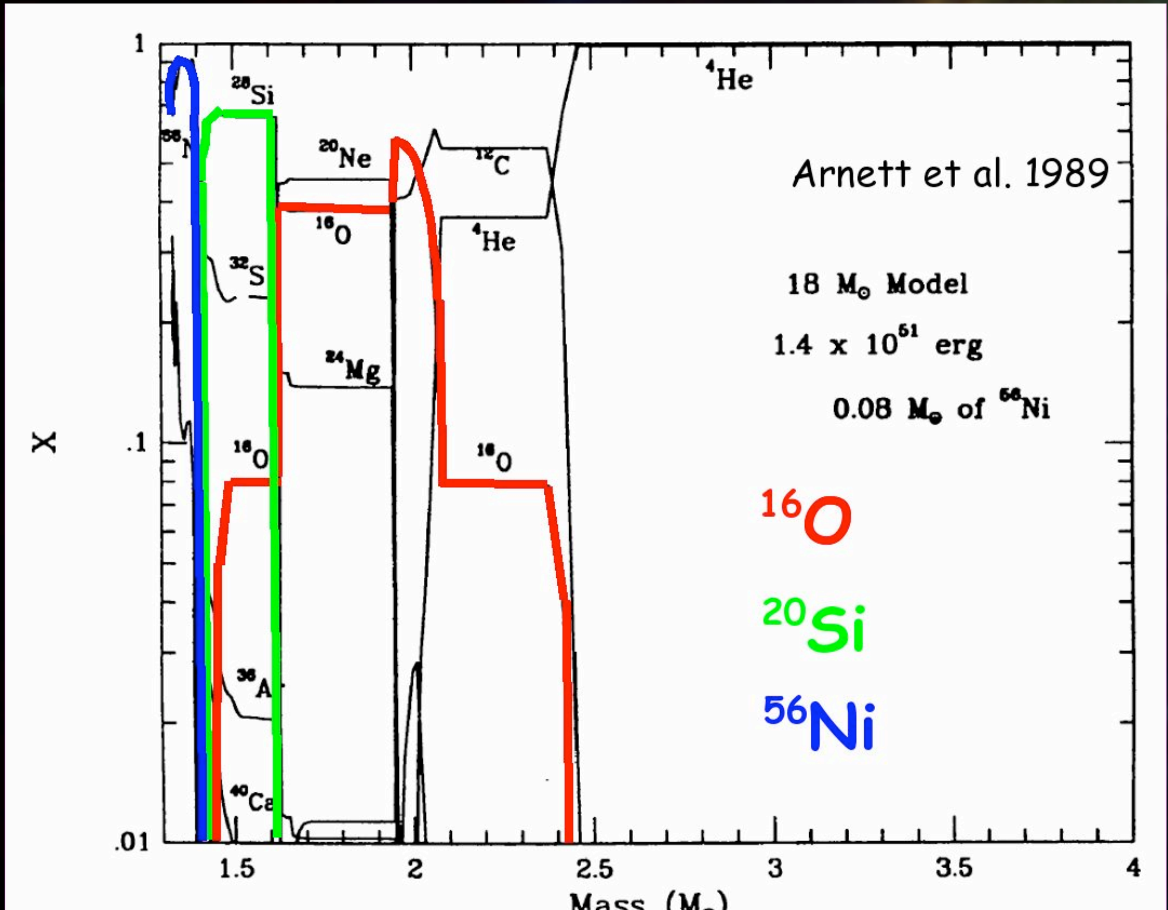
Hydro/Spectral Modeling
(also yesterdays talk by Daria Kosenko)

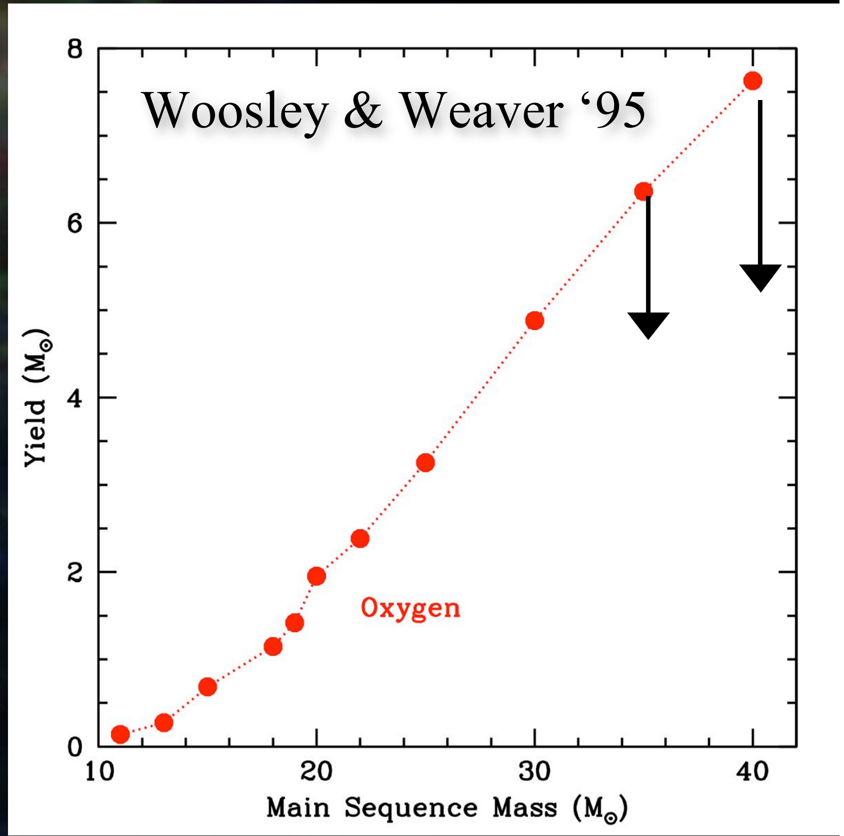




Tycho
Badenes et al. '05

Core-collapse Supernovae & SNRs

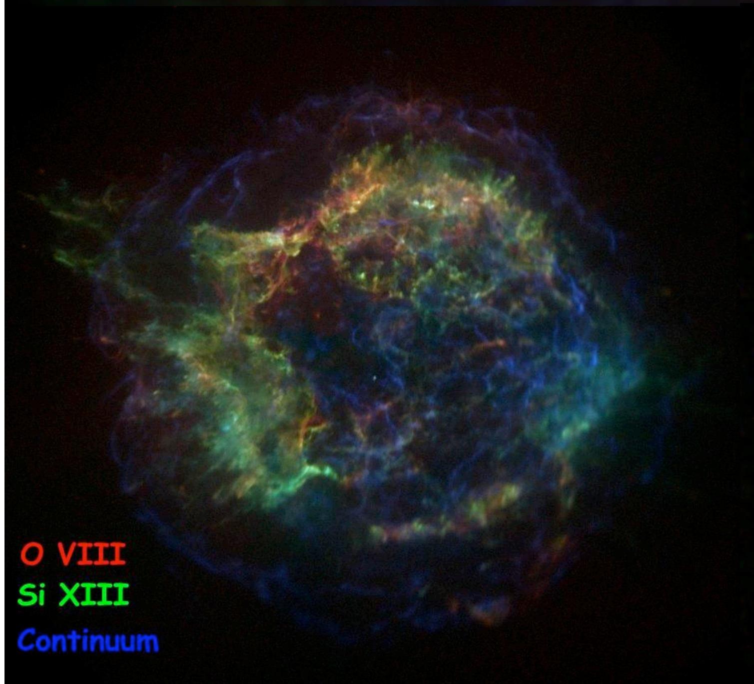




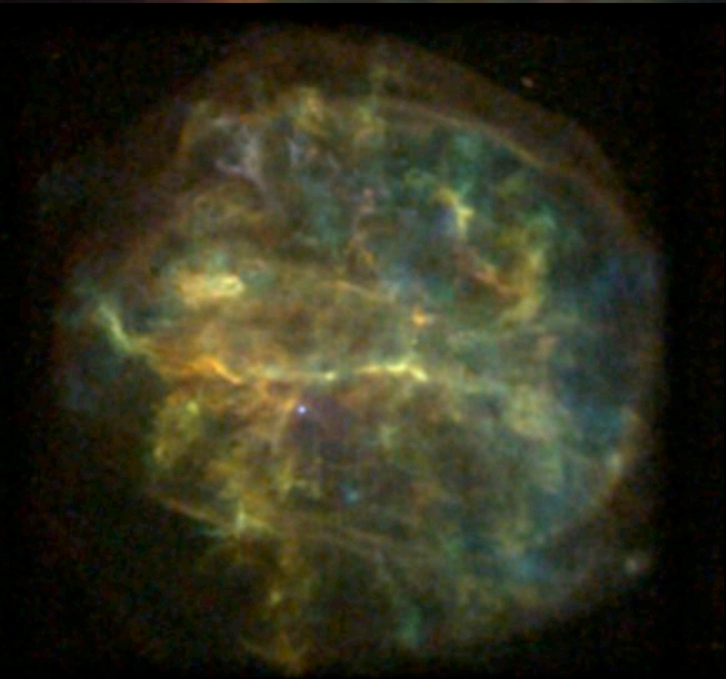
Core-collapse supernovae produce main source of oxyen

Some Oxygen Rich SNRs

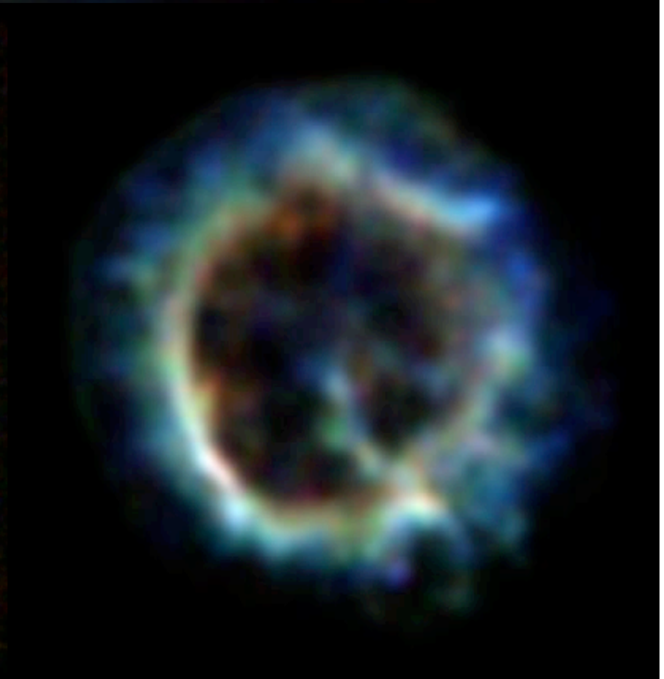
Must be remnants of the most massive stars $M > 20\ M_{sun}$



Cas A



G292+1.8



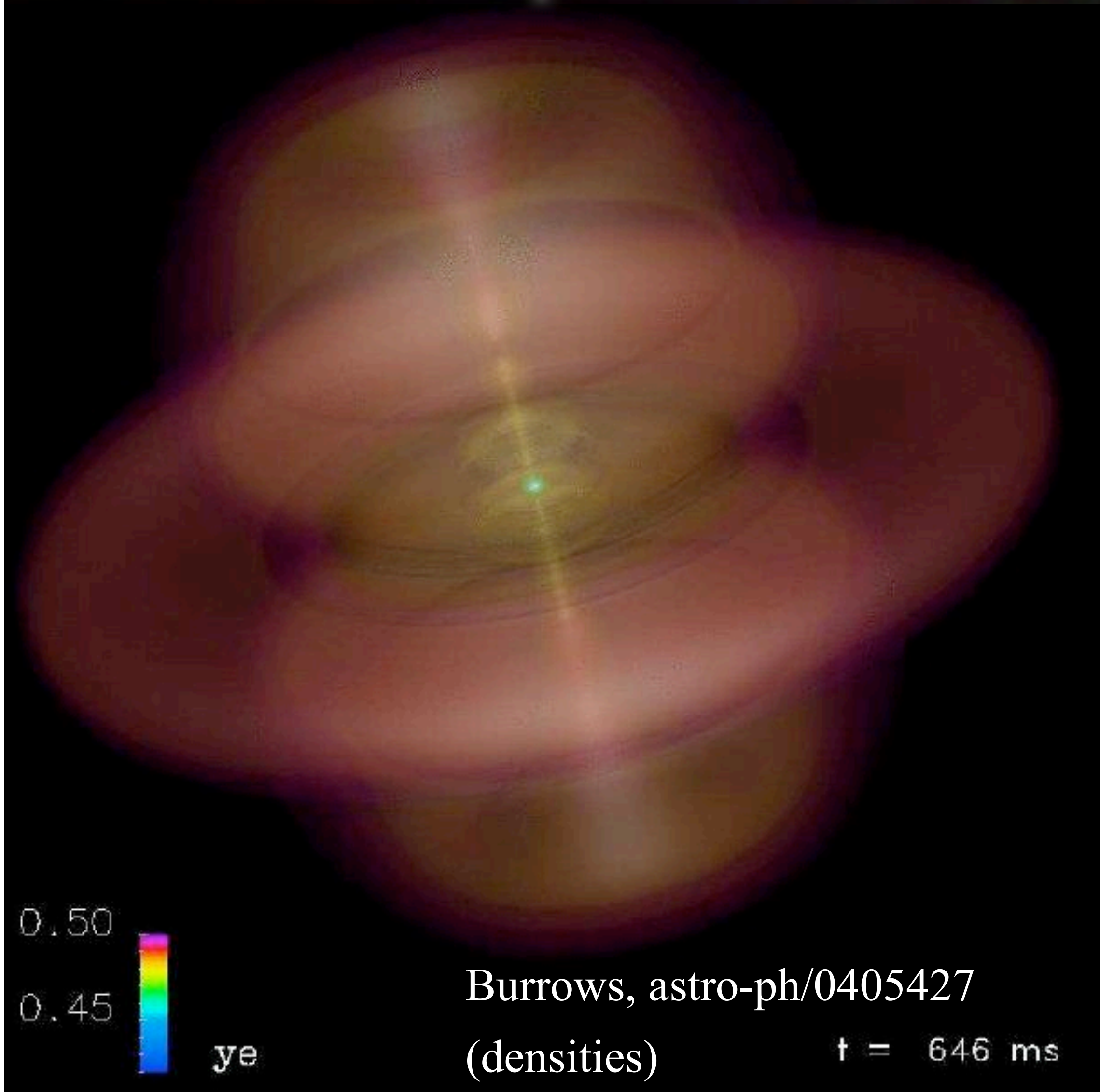
1E0102.2-7219
(SMC)

There are only a few known, besides these:
N132D (LMC) & Puppis A

Uncertainties concerning Core Collapse Supernovae

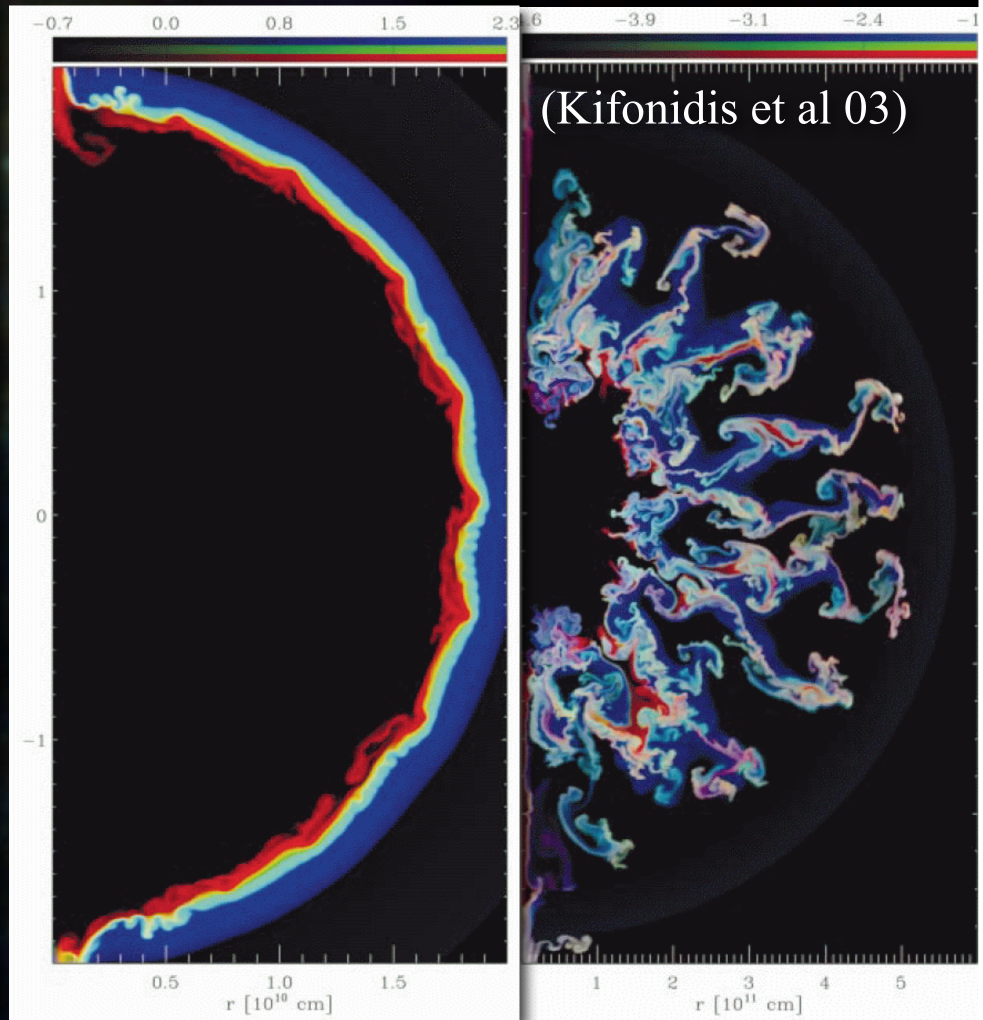
- So far no numerical model made that explain why the star explodes
  - Shock from “bounce” stalls
  - Additional input from neutrino’s does not provide sufficient energy
- What stars (MS mass) end with black holes, what stars neutron stars
- Do magnetic fields play any role? (magnetars)
- Is the explosion intrinsically asymmetric?
  - kick velocities neutron stars
  - extreme asymmetries: gamma-ray bursts (connected to Type Ib/c)
- What is the role of mass loss
  (shapes CSM, may alter nucleosynthesis yields)

Explosive Nucleosynthesis



Burrows, astro-ph/0405427
(densities)

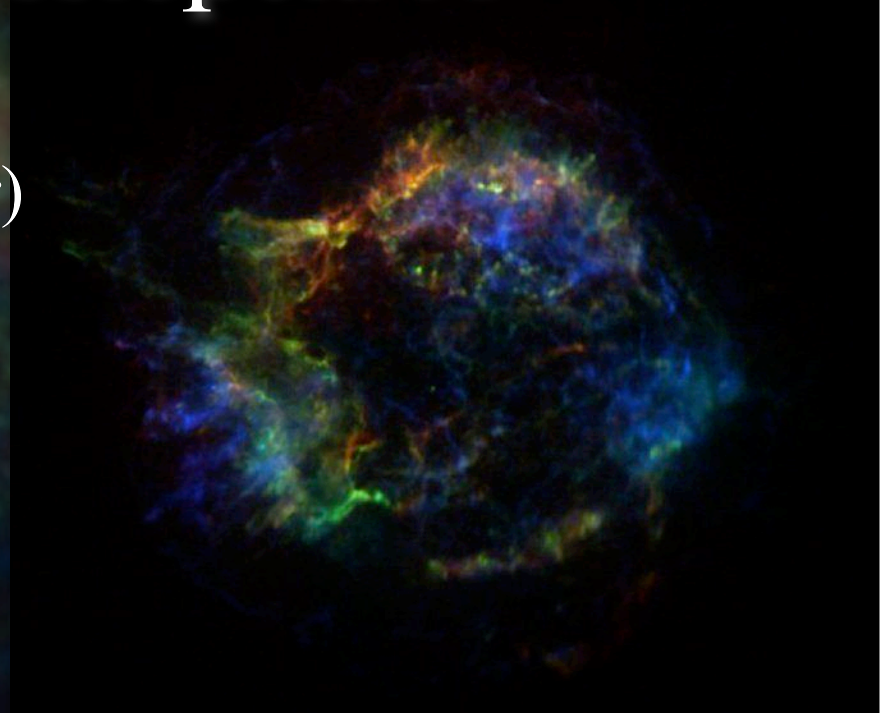
MHD: formation of jets?



(Kifonidis et al 03)

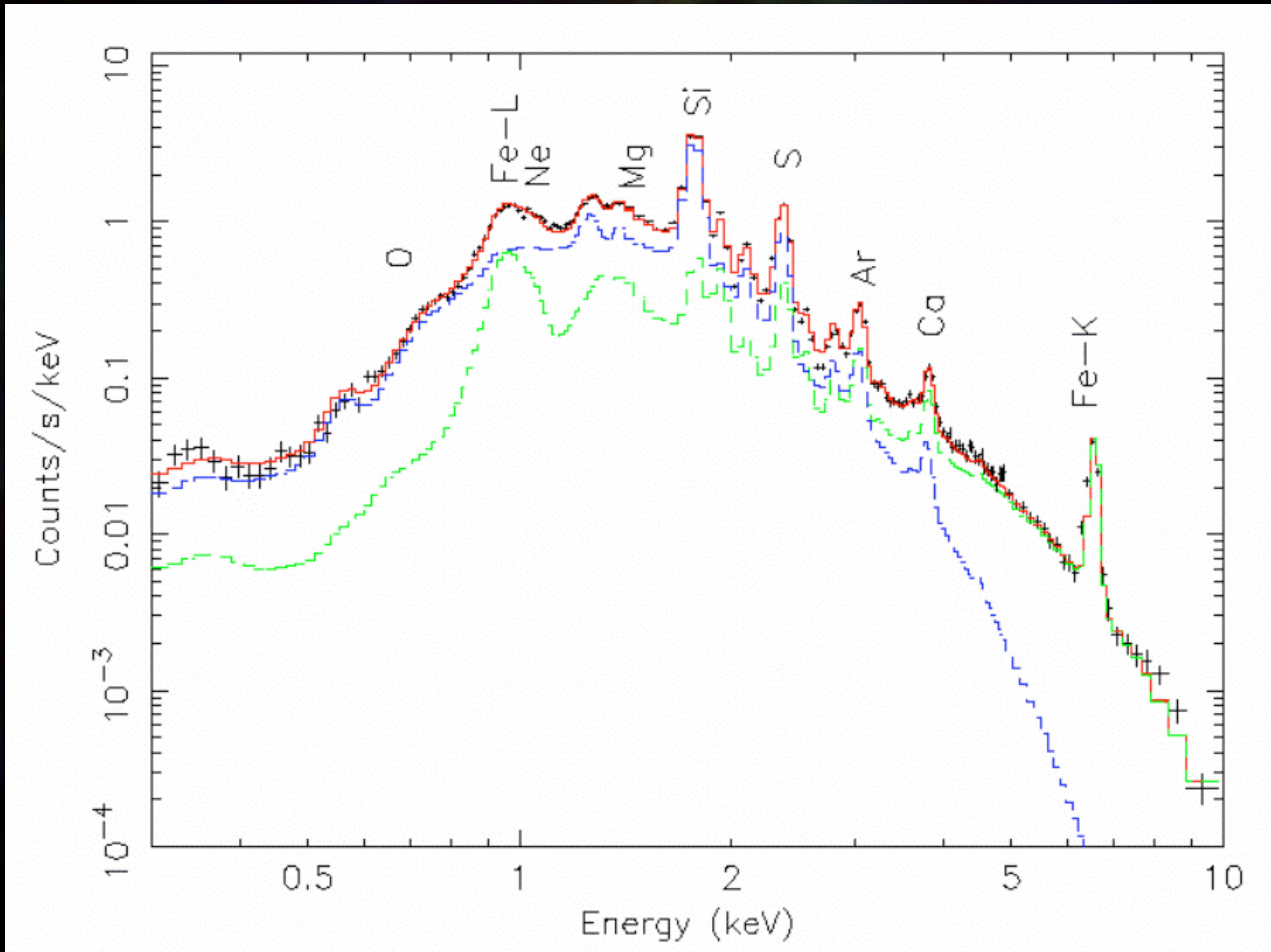
Evolution of fast fingers,
containing Ni
(can escape in Type Ib/c SNe)

A closer look at Cassiopeia A



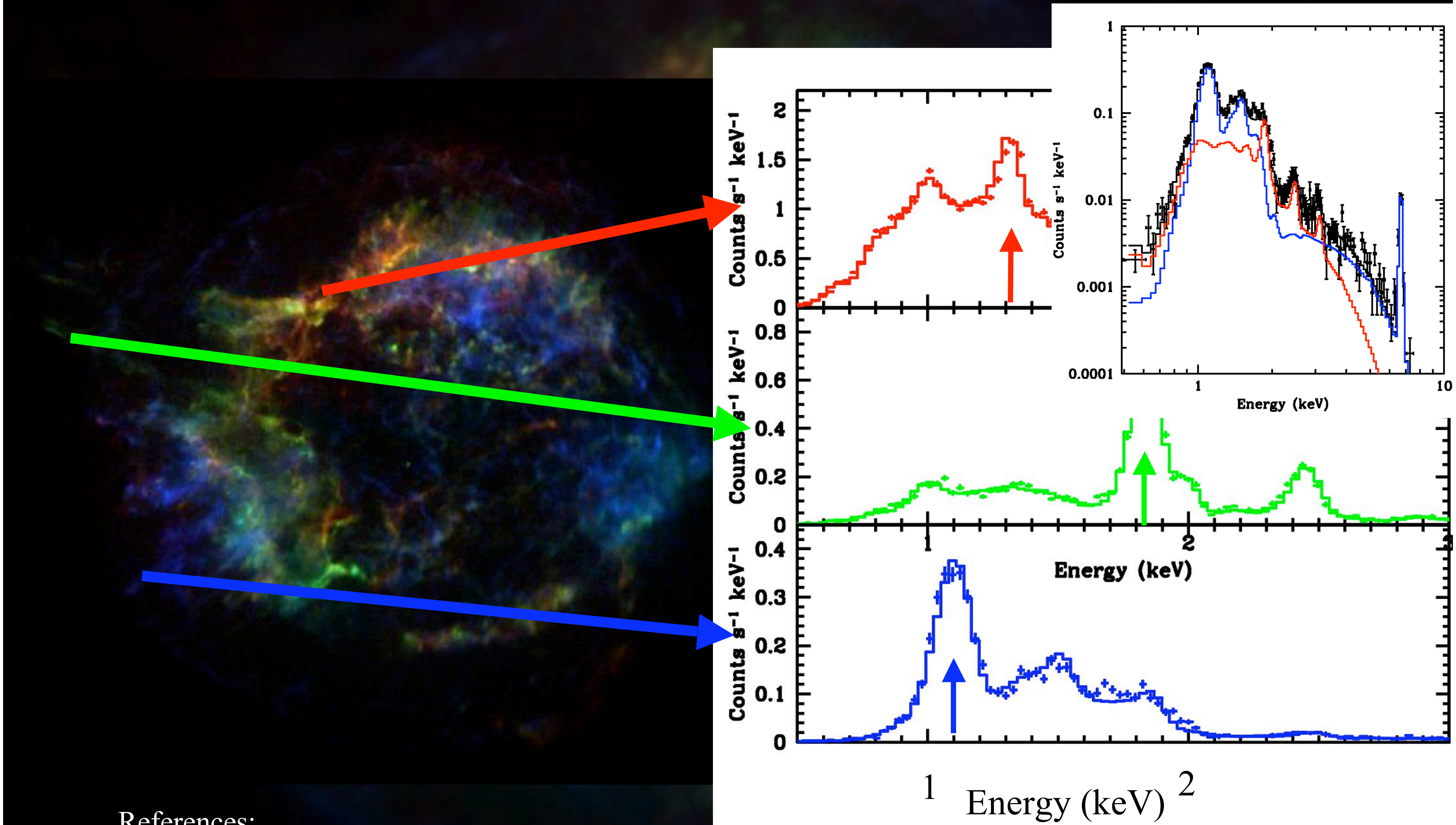
- Youngest known Galactic SNR (~320 yr)
- Brightest radio source in sky
  (2500 Jy @ 1 Ghz)
- Distance: 3.4 kpc (Reed et al. 1995)
- Size of ~5‘ → 5 pc (<v> ~ 8000 km/s)
- High blast wave velocity: 5200 km/s
  (Vink et al. '98,DeLaney & Rudnick'03)
- Oxygen rich, no hydrogen ejecta (optical emission)
  SN Type Ib?, Massive Star?
- X-ray emission dominated by ejecta
- Chandra discovery of probable neutron star (Tananbaum 1999)

X-ray spectrum of Cas A



Oxygen seems most important element (Vink et al. ‘96)

Chandra Imaging Spectroscopy



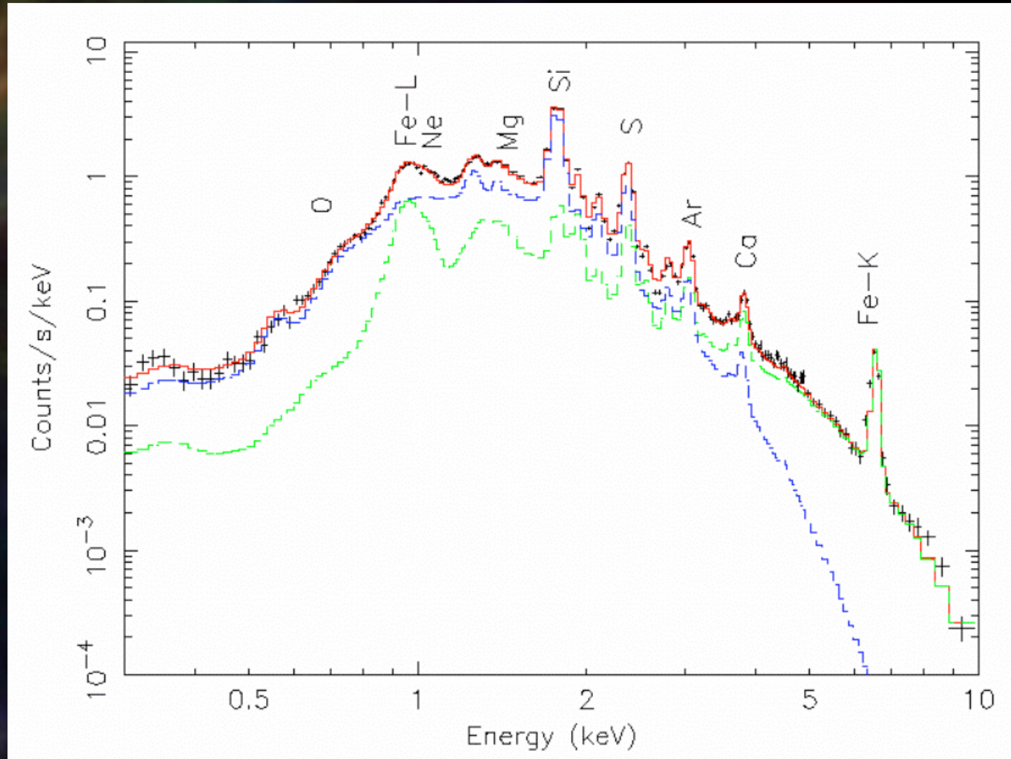
References:

Holt et al.'94, Vink et al. '99, Hughes et al. '00, Willingale et al. '02, Laming & Hwang '03

Iron plumes outside main shell!

Cas A's X-ray Spectral Modeling

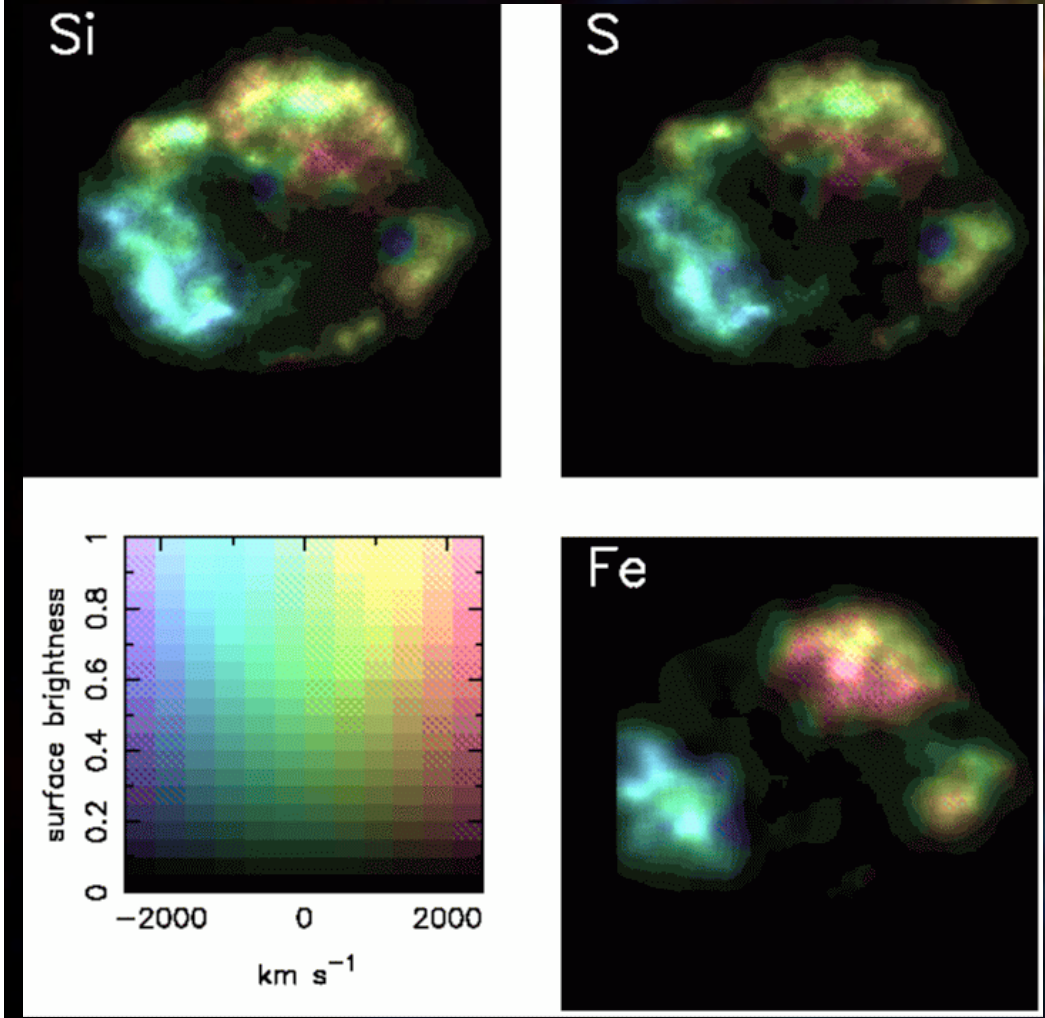
- Lack of Ne/Mg compared to models
- Dominant Si/S/Ar components
- Unlike G292/1E0102
- Possible reason: powerful explosion more burning of Ne/Mg to Si



Woosley & Weaver, '95 ; Woosley, Langer & Weaver, '93

	Willingale et al. '02	Vink et al. 96/99	S12A	S22A	S30A	S30B	Msun+wind loss
Ne/O	0.026	0.022	0.140	0.046	0.119	0.100	0.109
Mg/O	0.006	0.009	0.053	0.026	0.074	0.071	0.025
Si/O	0.043	0.039	0.441	0.161	0.039	0.079	0.123
S/O	0.026	0.026	0.378	0.080	0.004	0.022	0.071
Ar/O	0.007	0.008	0.127	0.015	0.001	0.004	0.014
Ca/O	0.005	0.009	0.071	0.007	0.004	0.003	0.010
Fe/O	0.022	0.014	0.071	0.017	0.008	0.009	0.174

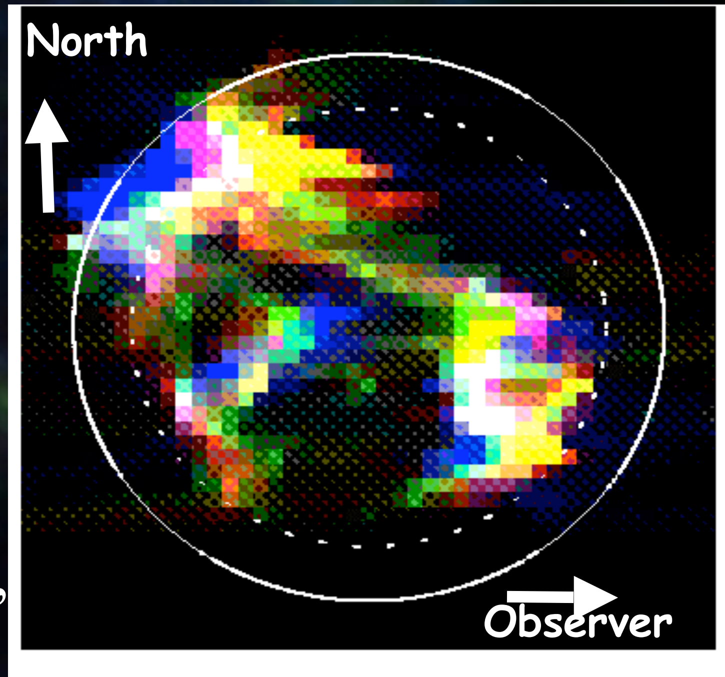
Cas A: Kinematics



XMM Doppler maps

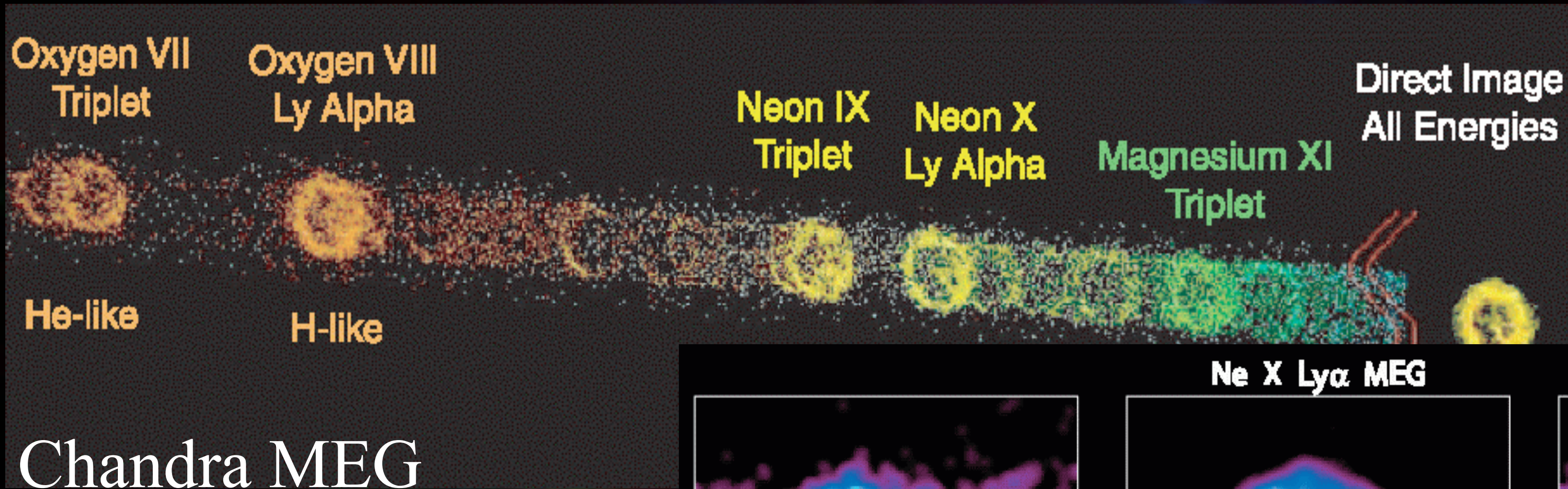
(Willingale et al. 2002)

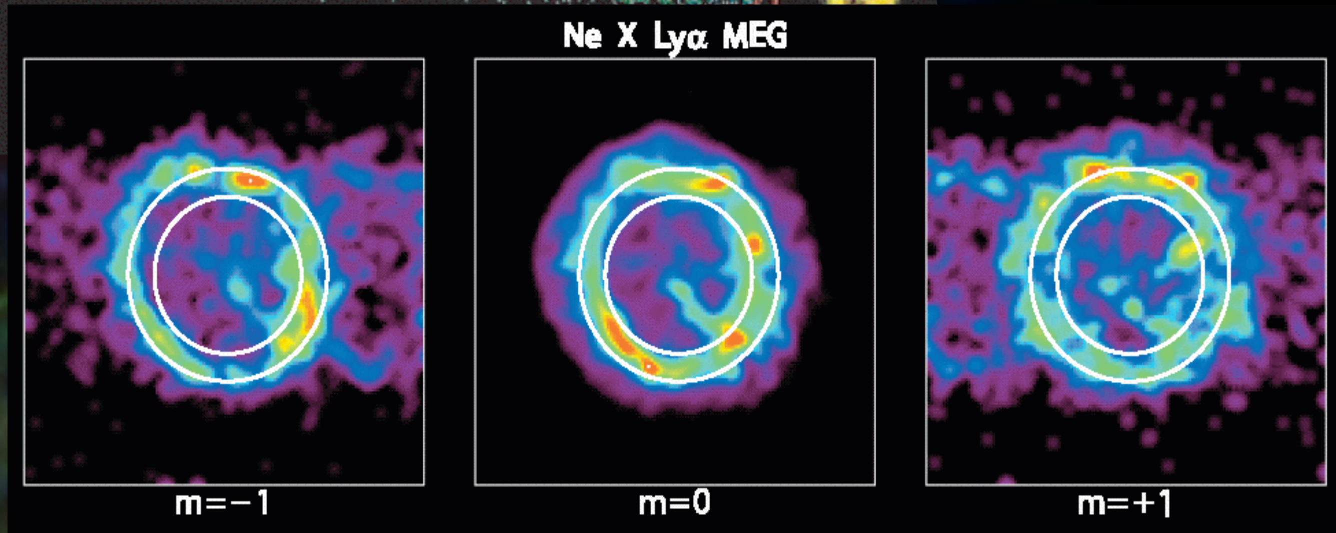
- Asymmetric velocity profile
- Velocities up to 2600 km/s
- Fe (deep layer) has overturned Si (both spatially and in Doppler space)



Reconstructed "side view"

Spectroscopic Imaging of 1E0102.2-7219



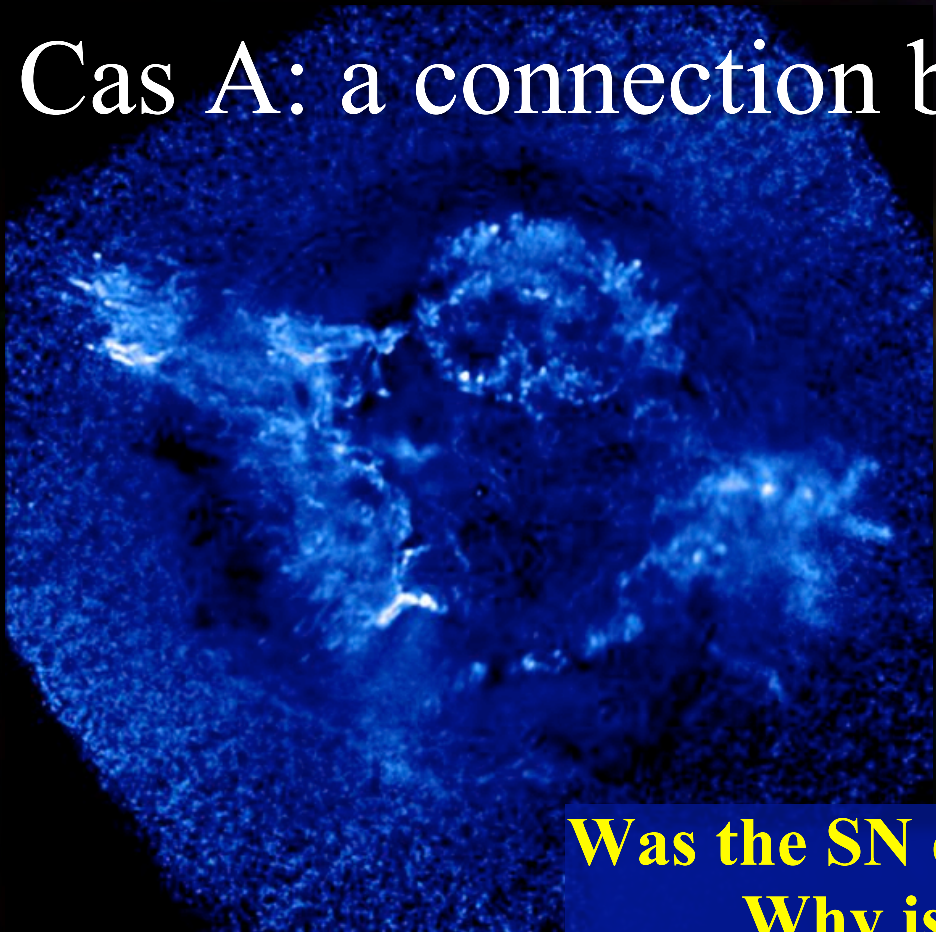


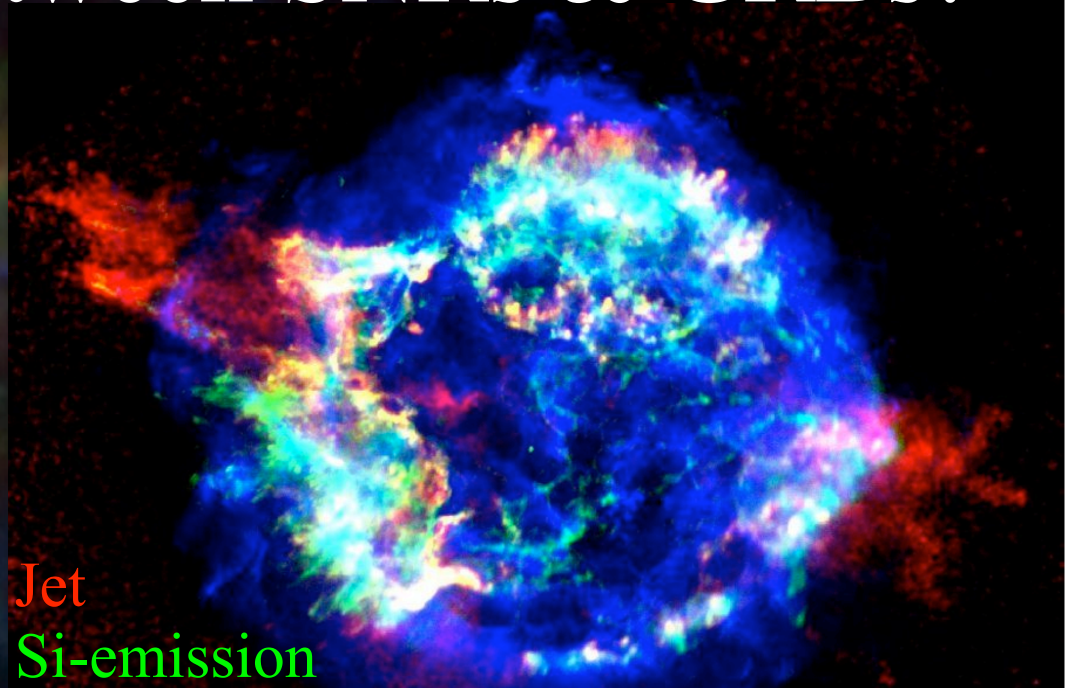
SMC remnant

- Oxygen rich (6 M_{sun}): i.e. massive progenitor (~35 M_{sun})
- In Chandra/MEG spectra: difference +/- orders (wavelength is mirrored/images not) → aspherical doppler shifts
- Bulk velocities ejecta ~ 1000 km/s
- Expanding donut rather than sphere?

Flanagan et al. 2004

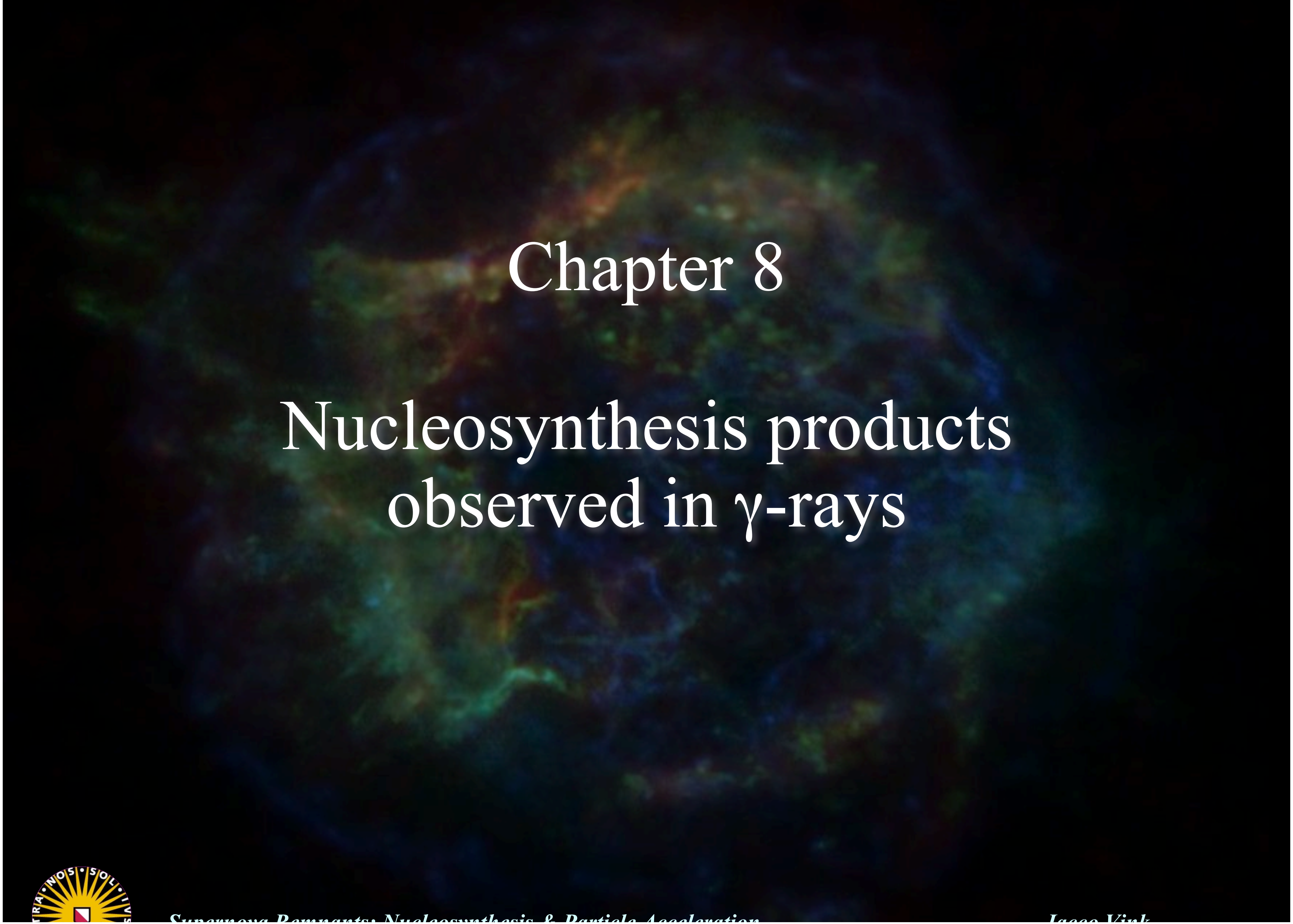
Cas A: a connection between SNRs & GRBs?





Was the SN explosion a weak GRB/X-ray Flash?
Why is jet Si-rich, not Fe (^{56}Ni) rich?

- Ratio of Si/Mg narrow band images: jet/counter jet (Vink '04, Hwang et al. '04)
- Jet spectrum shows near absence of Ne/Mg
- In jet Si/S/Ar abundance high
- Jet energy: ~1-5 x 10^{50} erg, 10%-25% of total energy!



Chapter 8

Nucleosynthesis products observed in γ-rays

Radio-active Explosive Nucleosynthesis

Line Emission:

^{56}Ni (8.8d, EC) → 158, 812 keV

^{56}Co (111.3d,EC/19% e^+ decay) → 847, 1238 keV

^{56}Fe

^{57}Ni (52hr, EC) → 1370 keV

^{57}Co (390d,EC) → 122 keV

^{57}Fe

^{44}Ti (85.4 yr) → 67.9, 78 keV

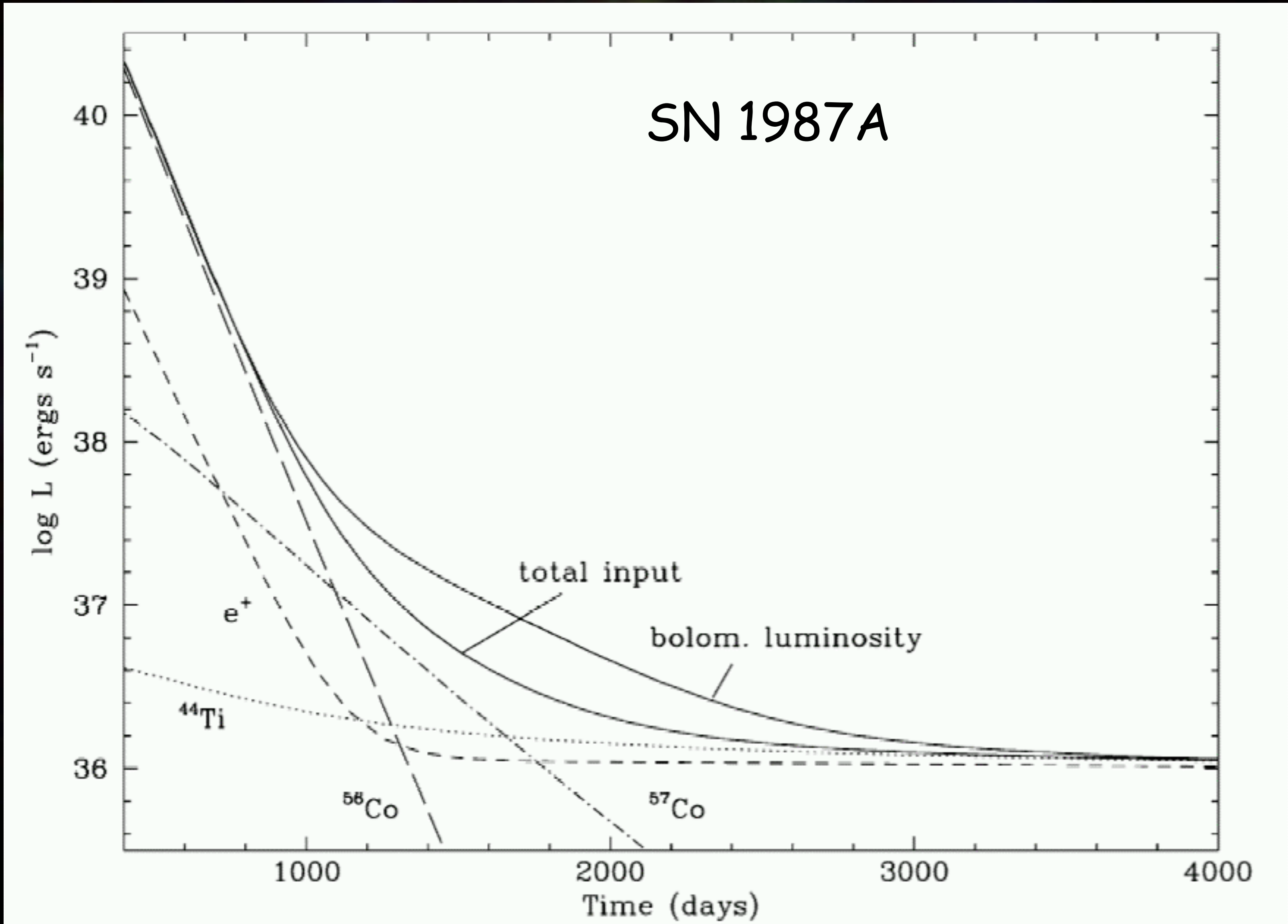
^{44}Sc (5.7hr, e^+ decay/1% EC) → 1157 keV

^{44}Ca

[e^+ e^- (from e+ decay) → 2γ] 511 keV

(annihilation time scales > 5 10^5 yr)

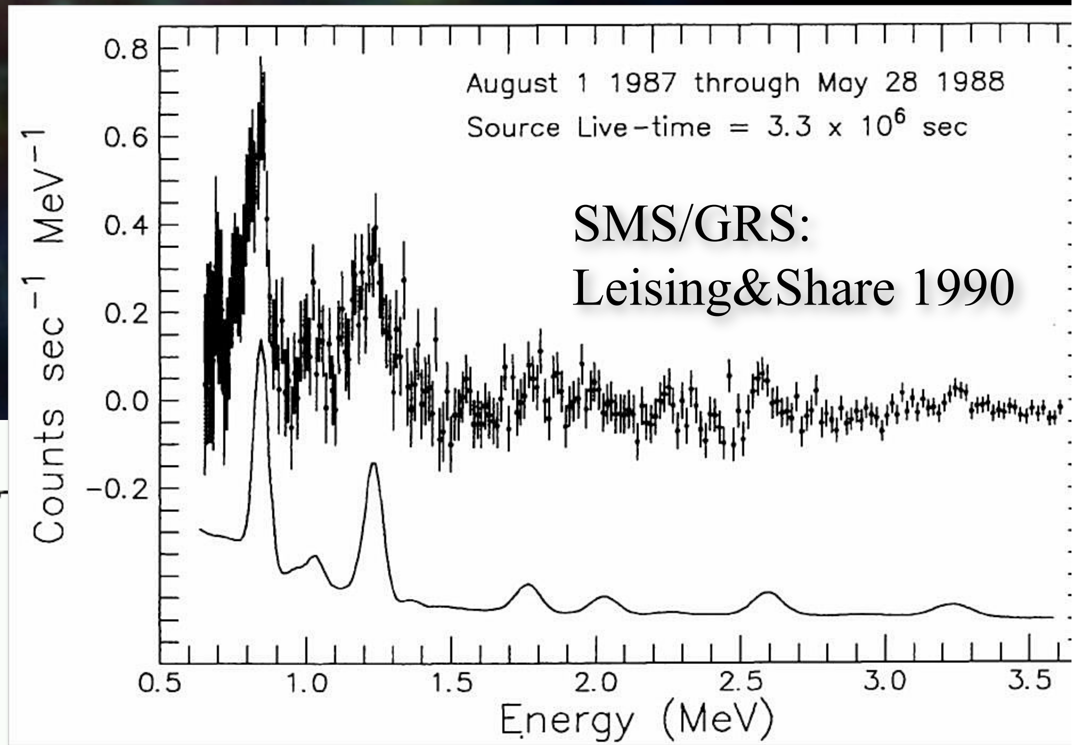
Indirect observation of radio-activity



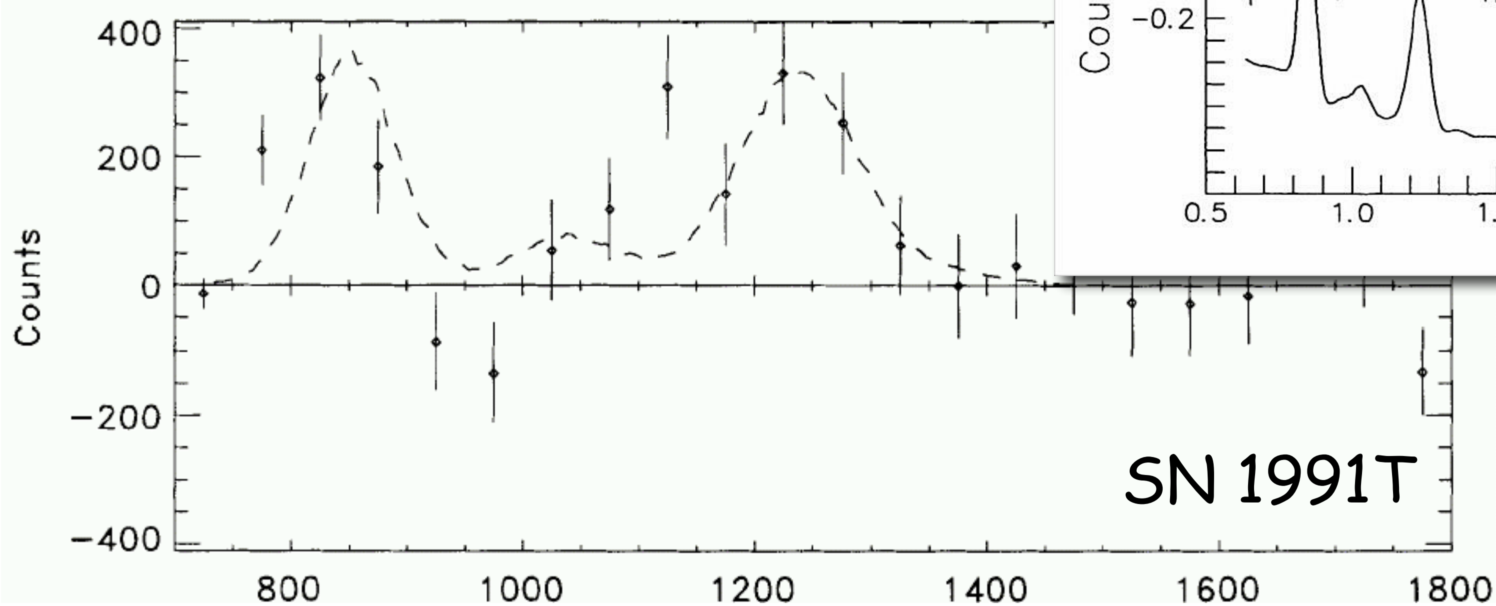
Franson & Kozma, 2002, NewAR 46, 487

Direct observations of radio-activity

SN 1987A : early emergence of ^{56}Co lines (847, 1238 keV)
Detected by various instruments
(e.g. Cook et al 1988, Mahoney et al., Matz et al. 1988)

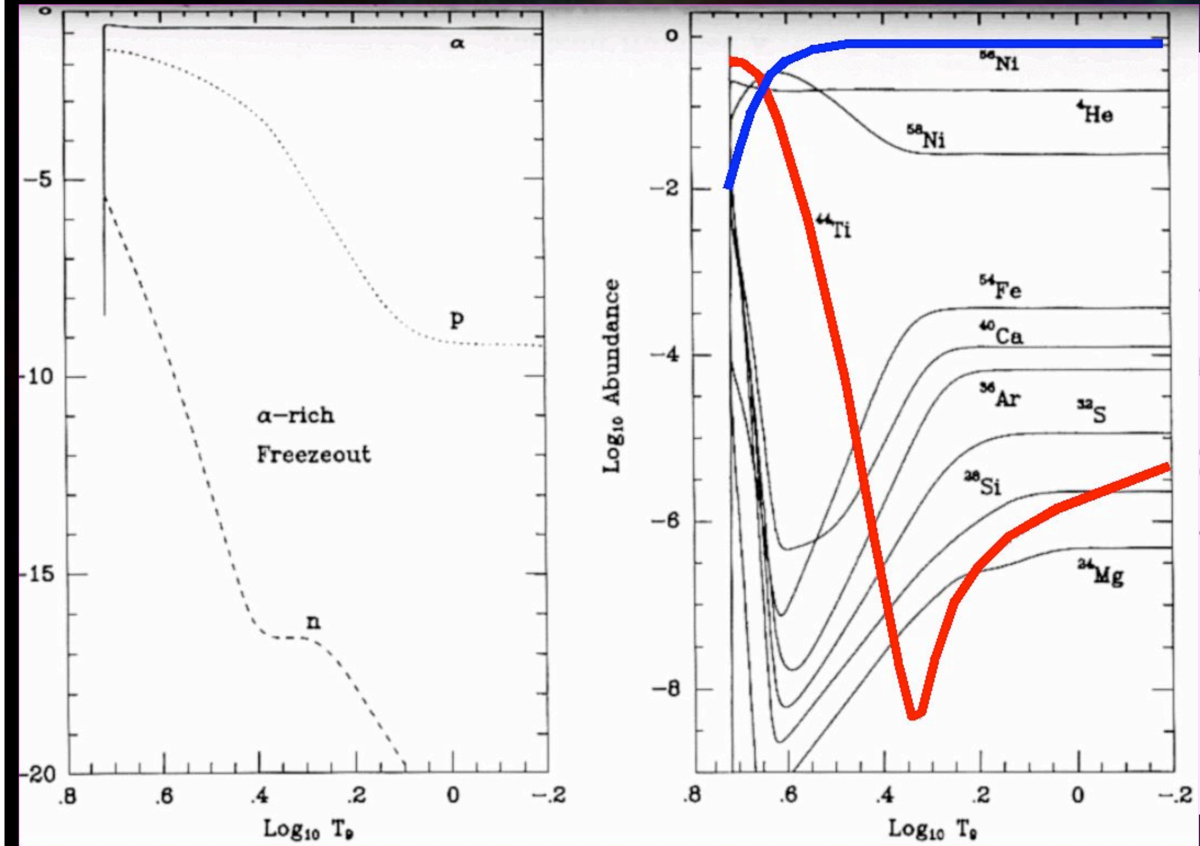


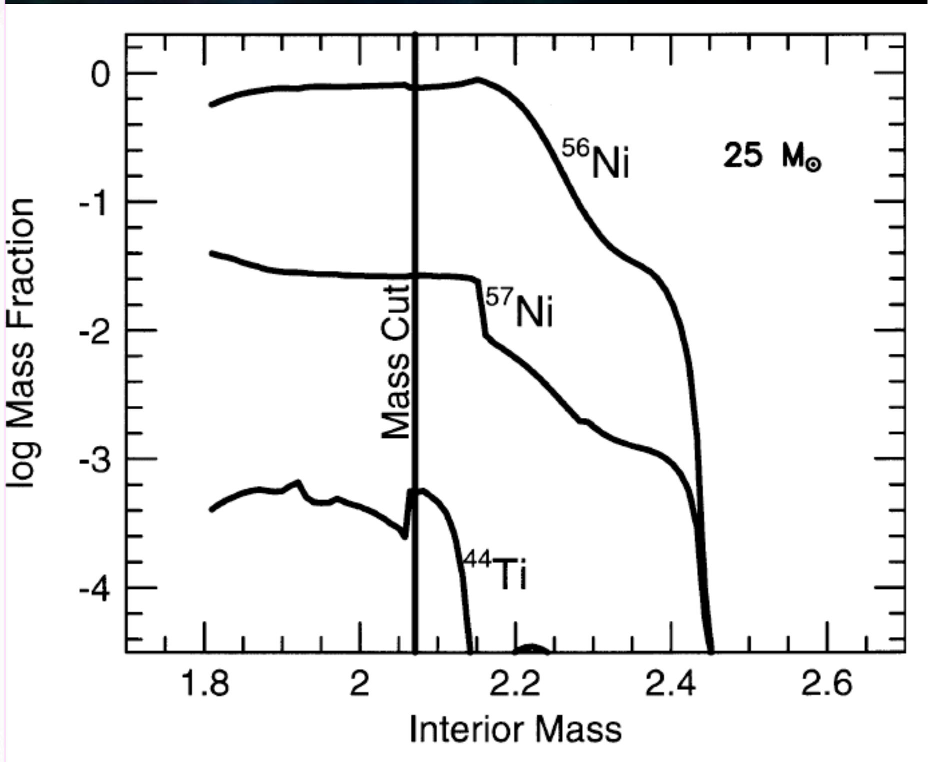
Marginal evidence for line emission from Type Ia **SN1991T** by COMPTEL
(Morris et al. 1995,1998)



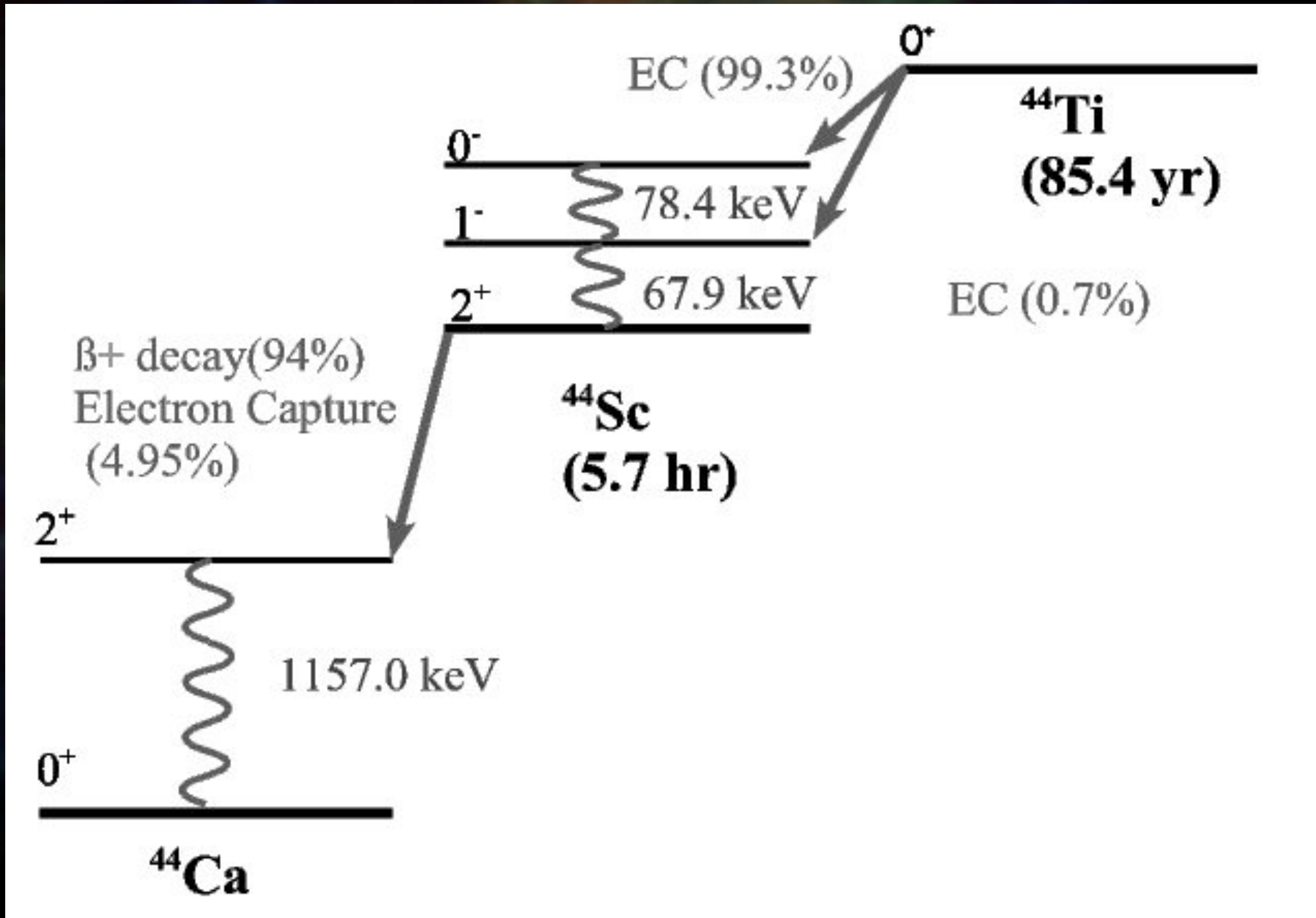
SNRs & Importance of ^{44}Ti

- Decay time ~85 yr: present in young remnants
- Much less abundant than ^{56}Ni (~0.07 vs 10^{-5}-10^{-4} $M_\odot$)
- Alpha rich freeze out product
  (thermonucleor burning in the presence of excess He)
- Amount sensitive to SN mass cut/energy/asymmetries



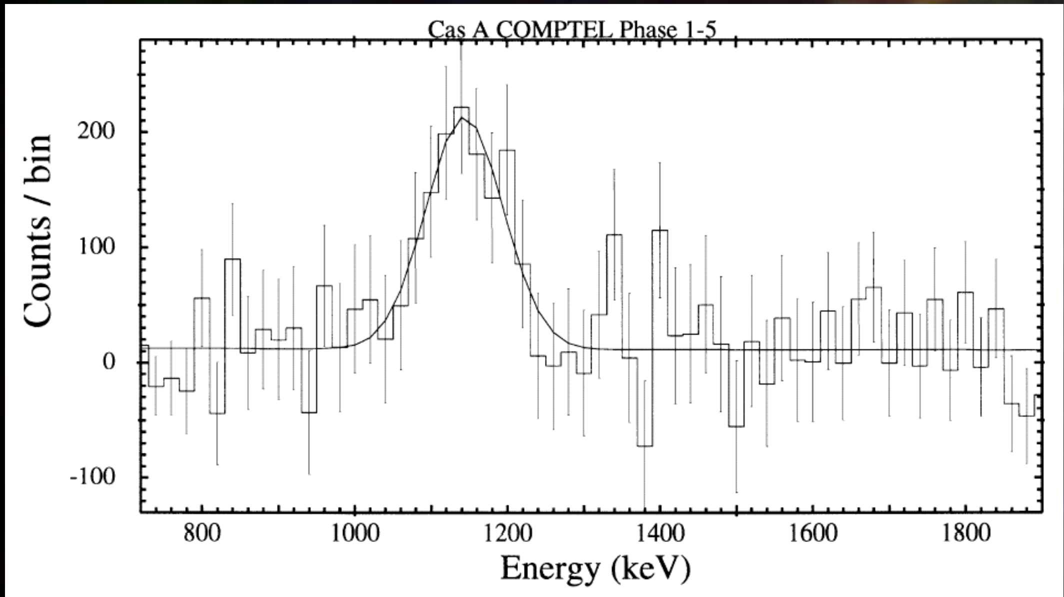


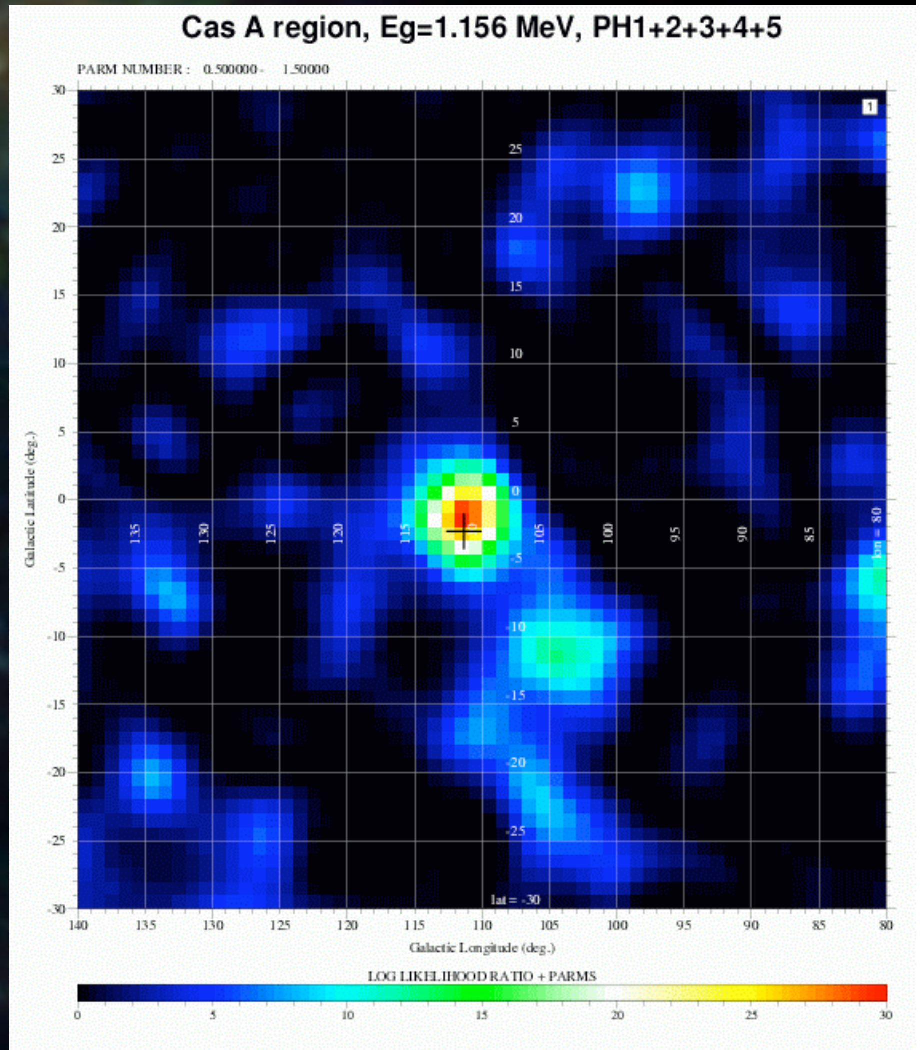
^{44}Ti Decay Scheme



^{44}Ti emission from Cassiopeia A

CGRO- COMPTEL





Flux: 7 x 10^{-5} ph/cm^2/s

(Iyudin et al. 1994)

Later revised to:

(3.3±0.6) 10^{-5} ph/cm^2/s (Iyudin 1997)

Detection of the 68,78 keV lines

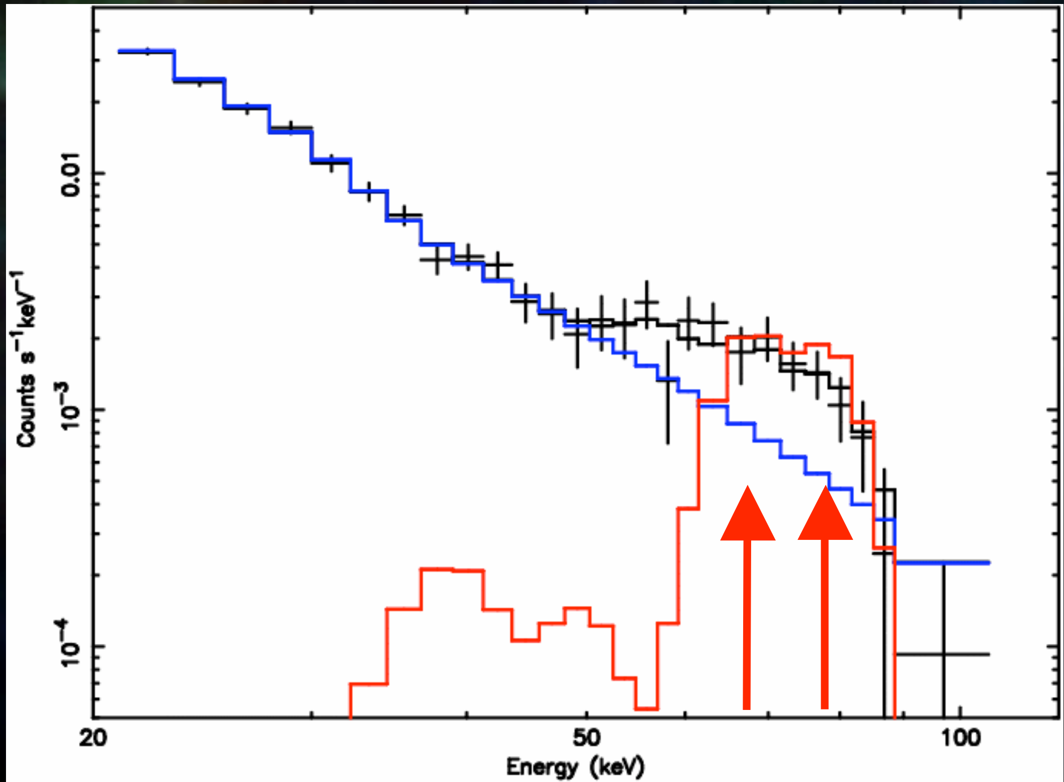
Attempts by CGRO-OSSE, RXTE-HEXTE & BeppoSAX-PDS

- Some 3σ upper limits close to COMPTEL flux

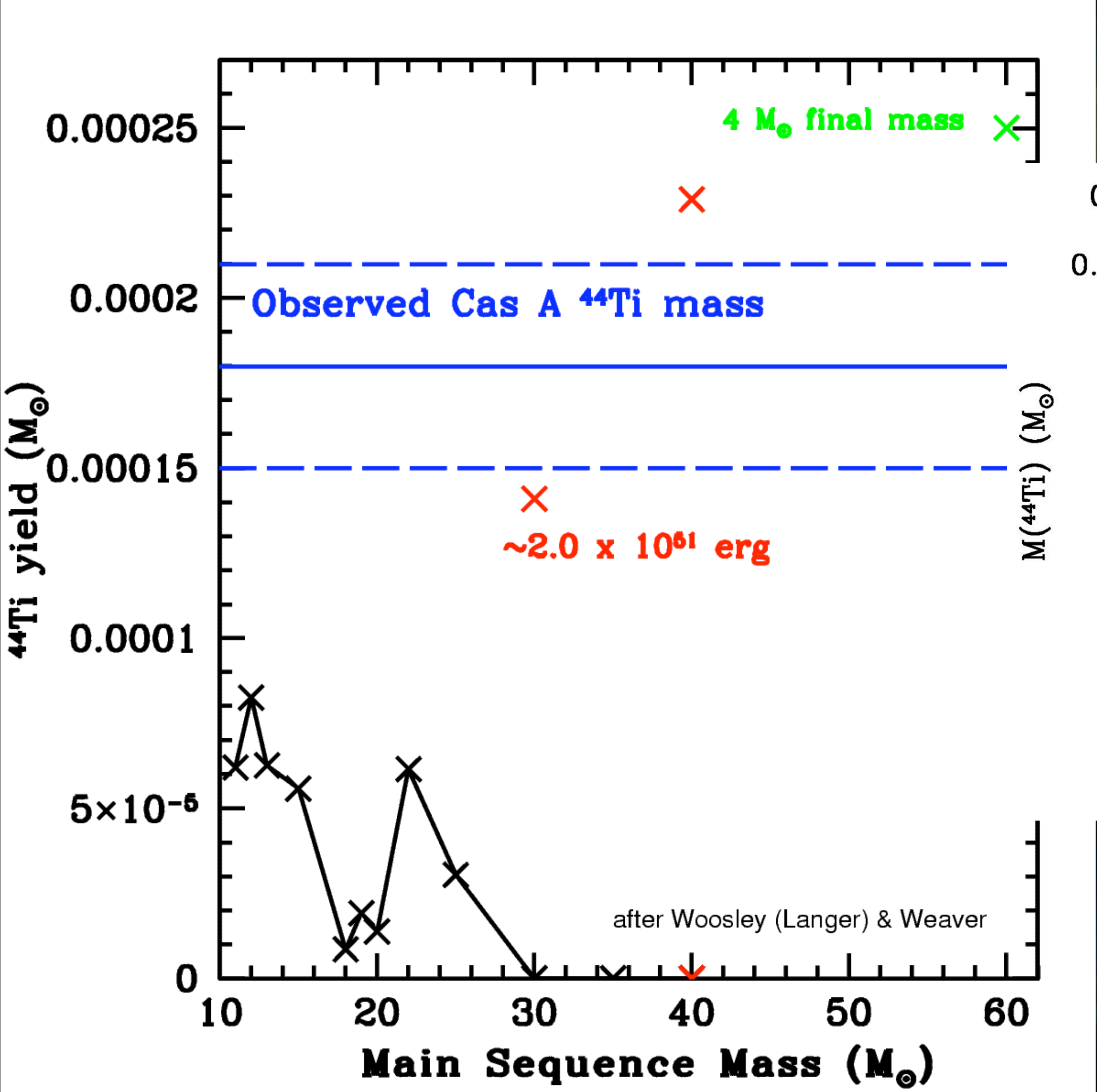
Finally detected by 500 ks BeppoSAX-PDS observation

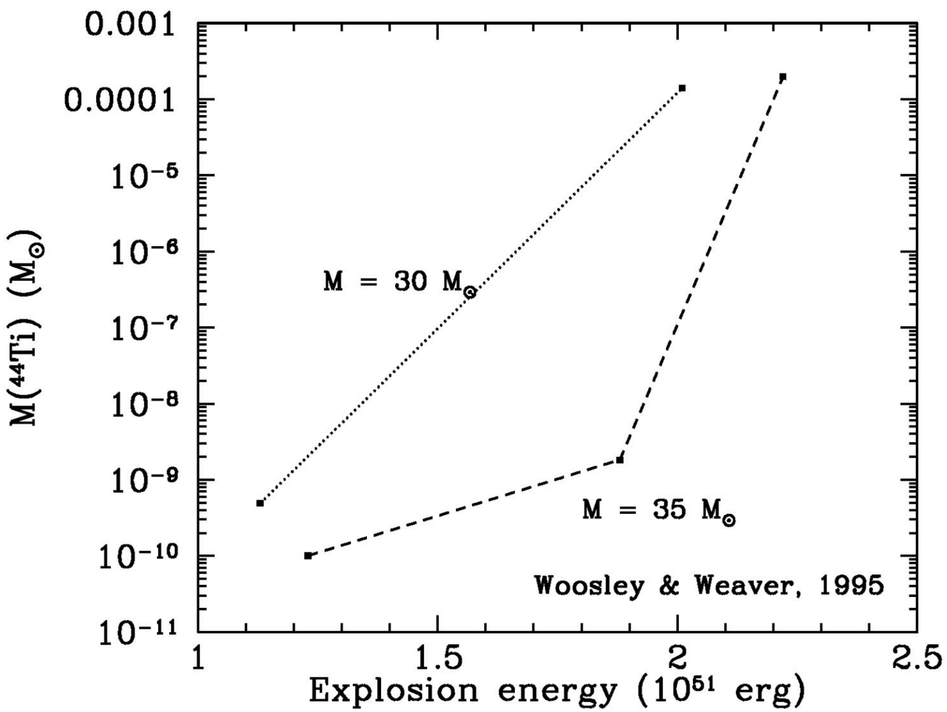
(Vink et al. 2001, Vink & Laming 2003)

Flux value and significance depends on continuum model.

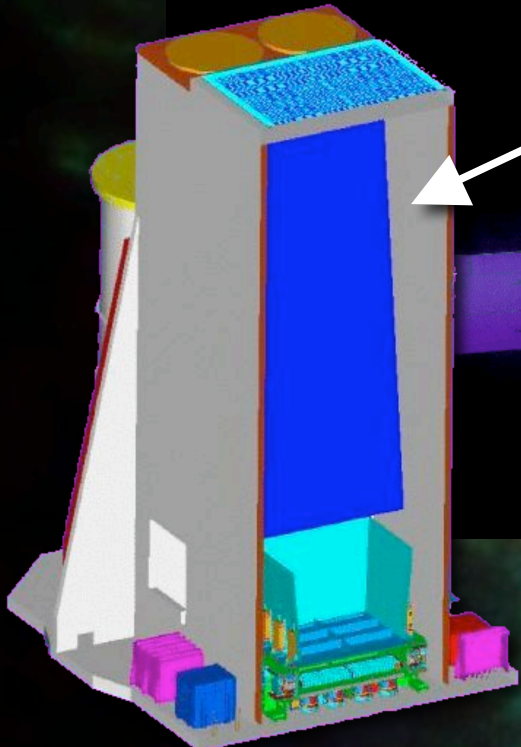


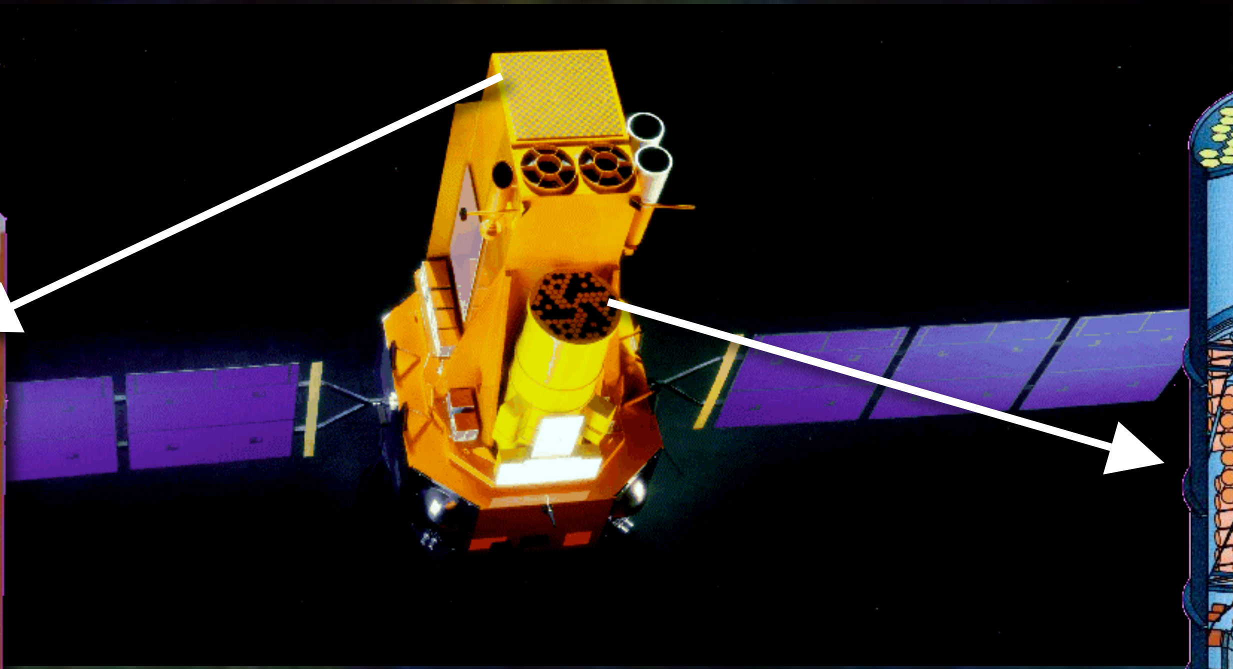
Nuclear decay and expected yields of ^{44}Ti

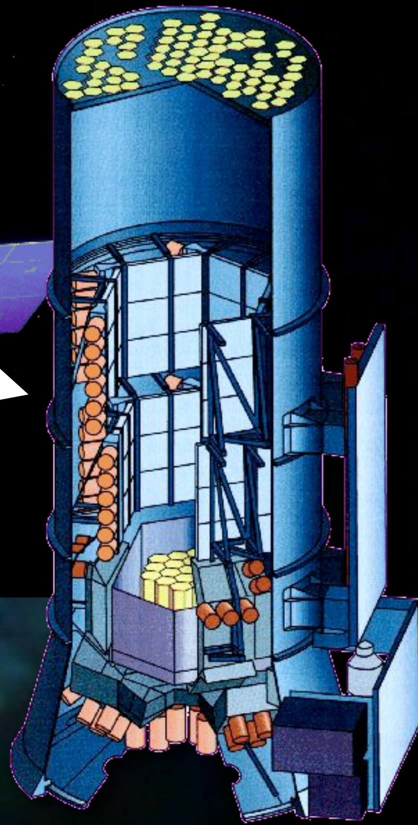




Integral observations of Cas A







Integral Imager (IBIS):
- 2 detectors: ISGRI & PICSIT
- FOV (fc): 9º x 9º
- Spatial resolution: 12' (FWHM)

Spectrometer (SPI):
- 19 (18) Ge
- Spectral res.: 3 keV @ 1.7 MeV
- FOV (fc): 16 degrees
- Spatial resolution: 2.5º (FWHM)

Primary Goals of the observations

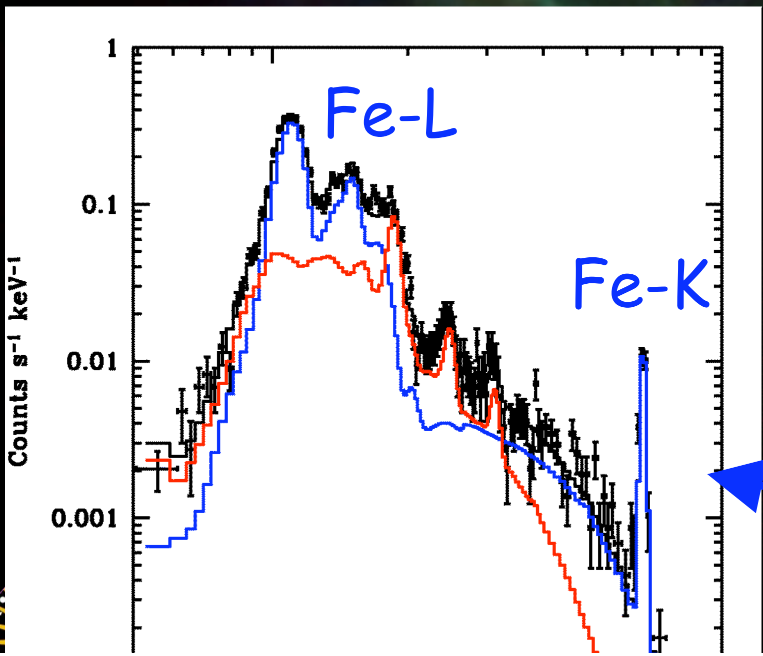
- Further constraining ^{44}Ti line flux and yield

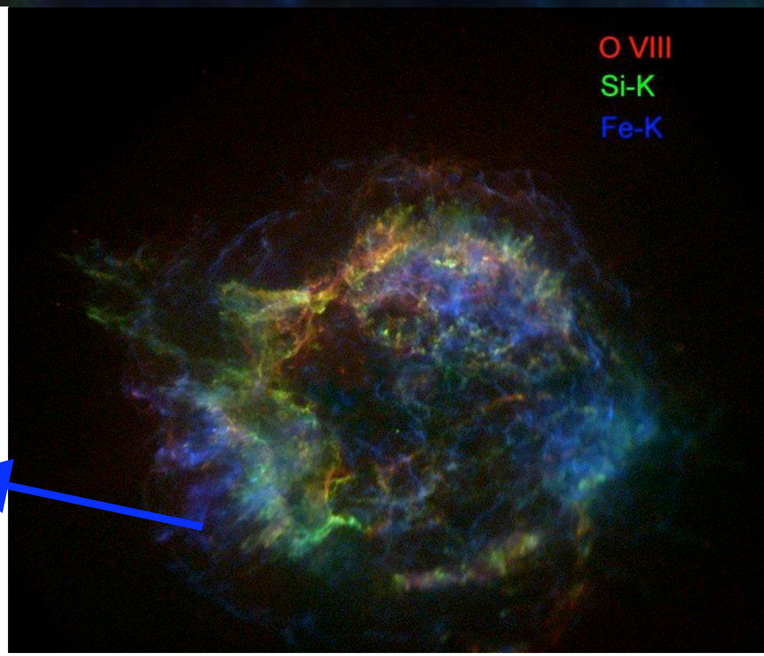
IBIS: - measure 68 keV & 78 keV line flux

- constrain continuum up to and beyond 90 keV (does it steepen?)

SPI: - detect the 1157 keV line

- detect or constrain velocity broadening (connection with fast moving Fe seen in X-rays?)





Cycle 1+ IBIS Observations

Cycle 1 completed in March 2004: 1.5 Ms

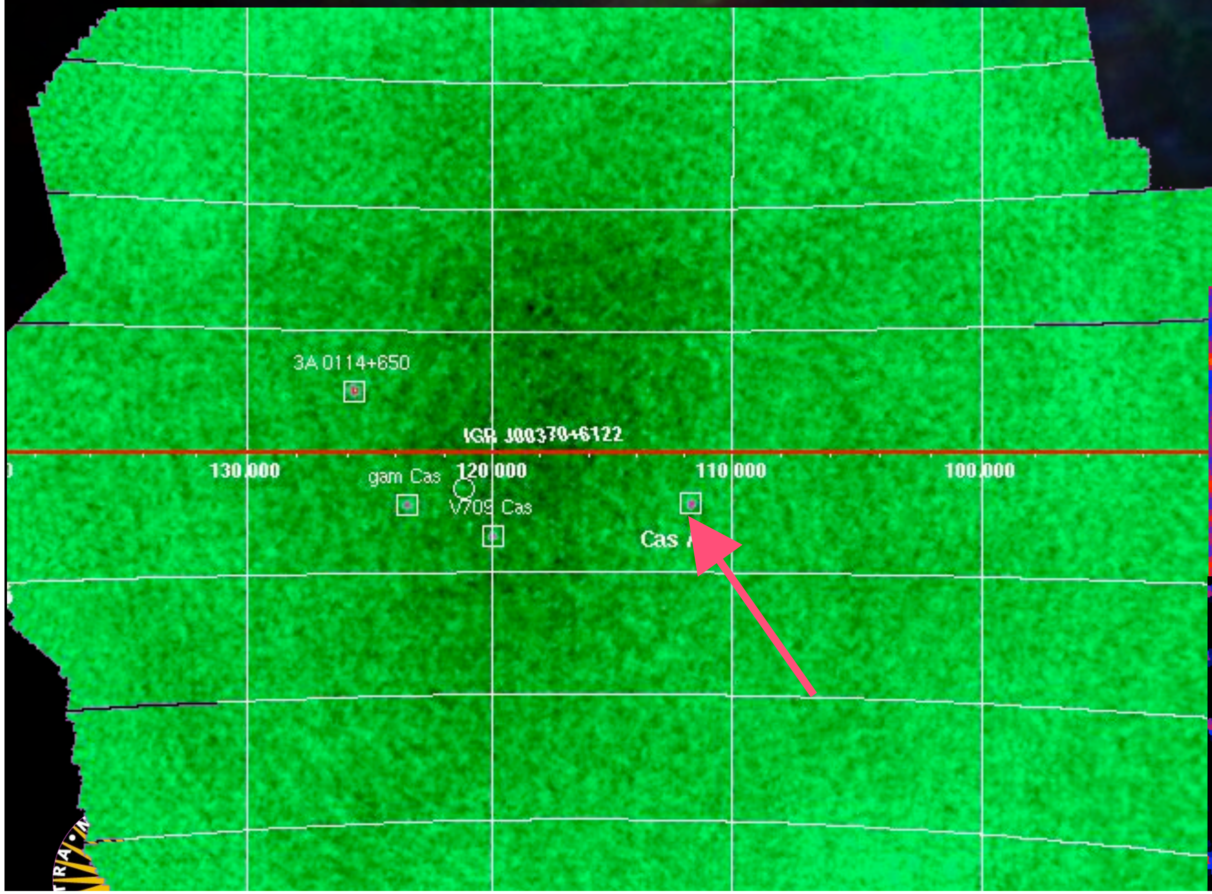
Cycle 2 ongoing: 1.5 Ms total, 0.3 Ms observed

First IBIS results on serendipitous sources:

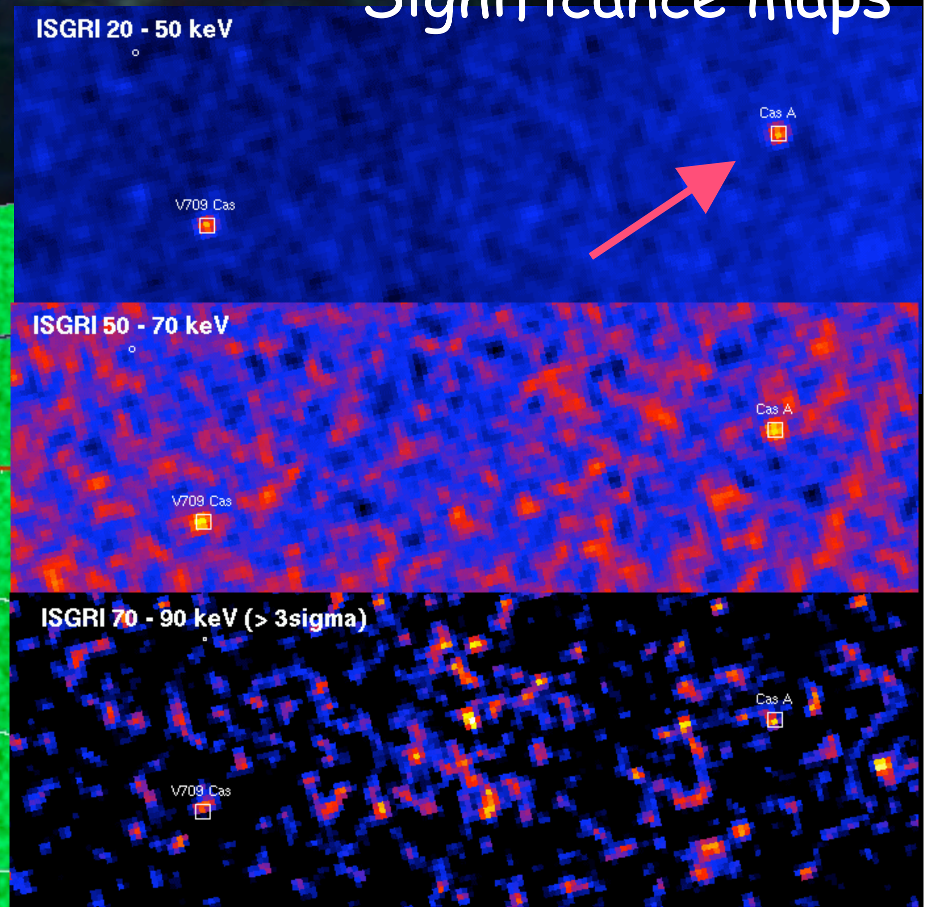
e.g. den Hartog et al.: ATel 281: IGR J00370+6122 -A new high-mass X-ray binary

den Hartog et al.: ATel 293: Hard X-ray detection of AXP 4U0142+614

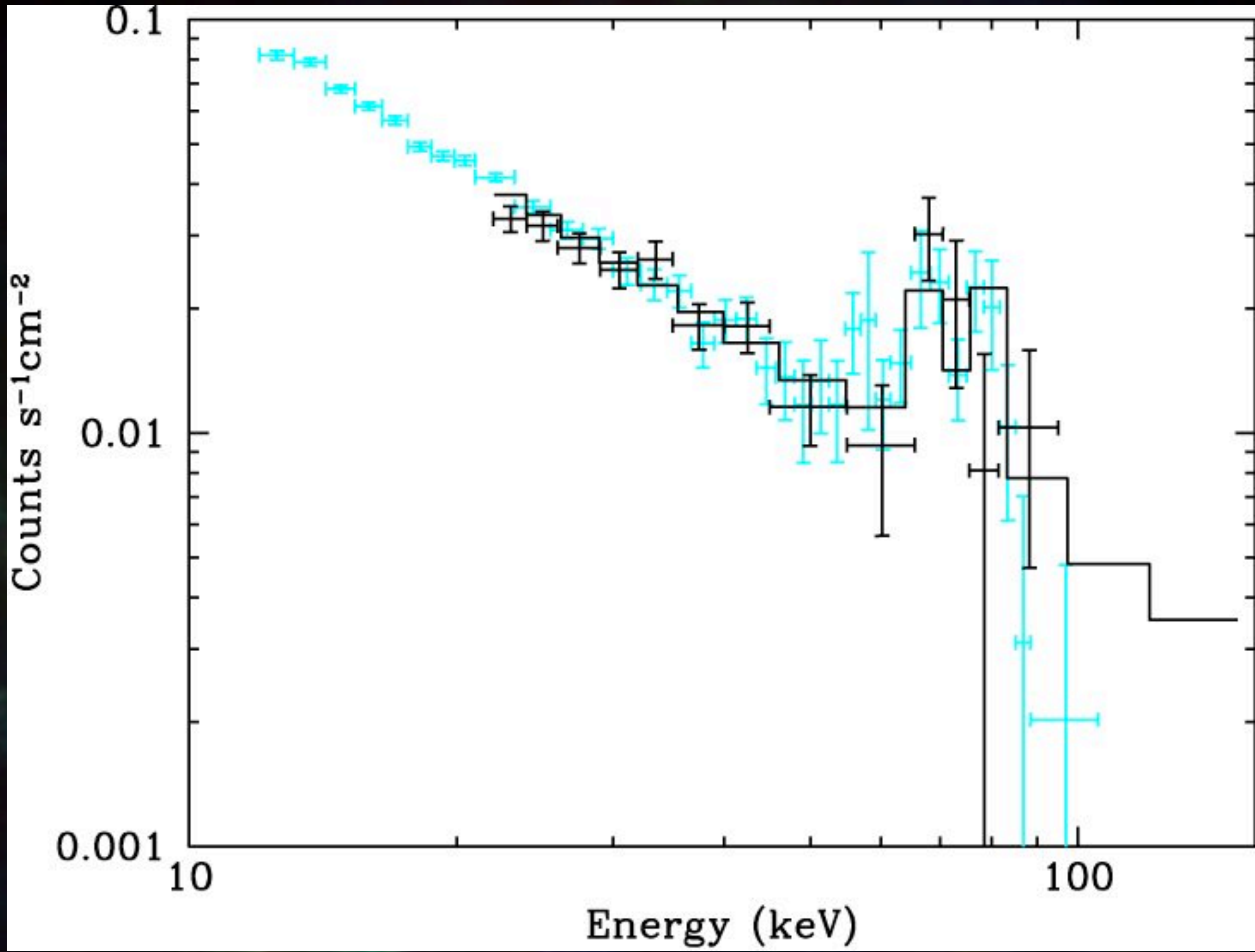
IBIS-ISGRI maps reveal Cassiopeia A up to 90 keV:



Significance maps



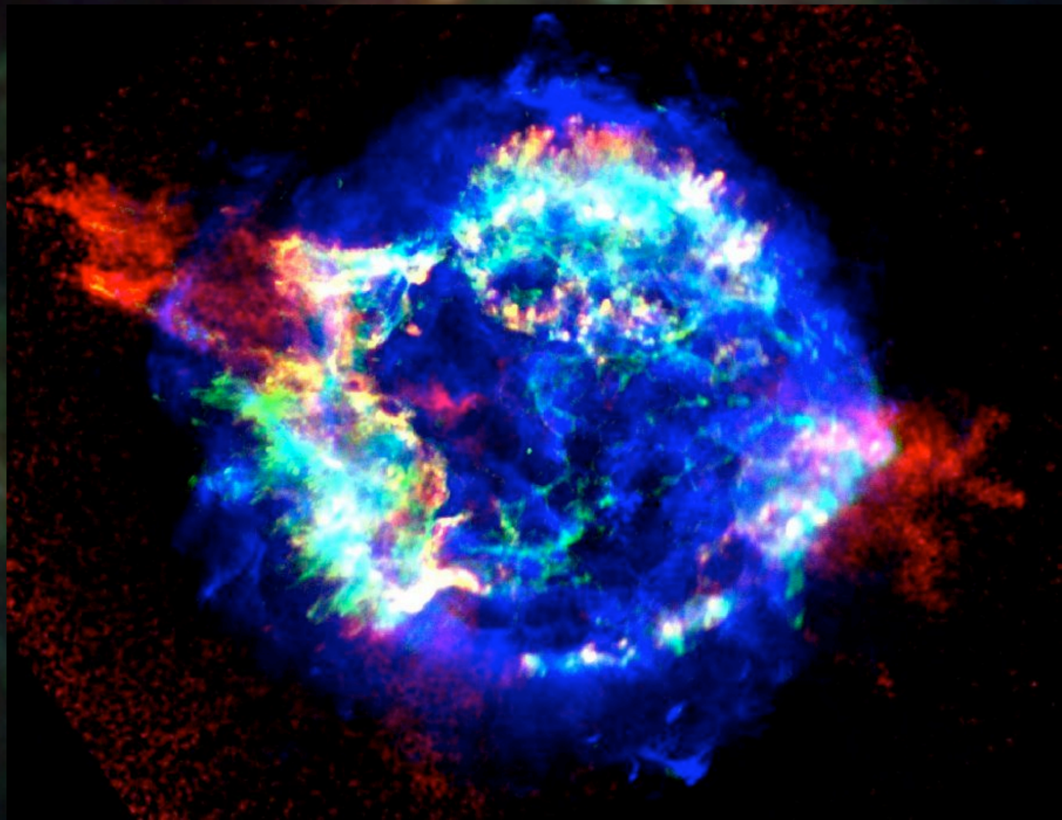
INTEGRAL/ISGRI Spectrum of Cas A



F= (1.9+/-0.4) x10^{-5}ph/s/cm^2

Latest are being analyzed:
preliminary analysis suggest independent detection of both lines

The End



If you want to work in this field:
A post-doc and a PhD position available in Utrecht